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DYNAMIC LIFE CYCLE ASSESSMENT FOR ELECTRIC PROPULSION WITH NET-ZERO FUELS

by

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degree of Doctor of Philosophy

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This thesis is the result of the author’s original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

To my Lord,

To my family, Juhyun Park, Sanghee Lee & Heena Park

ABSTRACT

In recent decades, Life Cycle Assessment (LCA) has been widely adopted as a method to determine the holistic environmental impacts of products and systems across various industrial and academic sectors. The methodological soundness of LCA has been demonstrated during this period. Although the marine industry was a latecomer to LCA, with few studies reported until 2000, there has since been a gradual increase in the number of LCA applications for marine ships and fuels.

Initially developed as a standardised model to assess the holistic environmental impacts of static activities, LCA has been criticised for its inadequacy when applied to the maritime sector, where ships are subject to dynamic changes. Shipping activities operate in an ever-changing environment of wind speed and direction, solar radiation, ship speed, load, routes, and voyage schedules. As a result, it is essential to estimate the environmental impact of ships on a real-time basis.

This thesis highlights the research gaps inherent in the conventional LCA method and their applications in the maritime sector, which can be summarised into two fundamental issues: 1) the traditional LCA is overly dependent on past data, and 2) their results are deterministic while no real-time processes are involved. To address these gaps, this thesis introduces Dynamic LCA, which comprises two packages of LCA models: Live-LCA and Real-time LCA. The effectiveness of these LCA models was evaluated through a series of case studies.

Live-LCA was applied to ships using solar PV systems, revealing a difference of up to 44% in the environmental impacts of the case ship compared to the traditional LCA. This case study also contributed to demystifying the lifecycle impacts of PV systems for marine applications. The second case study with Live-LCA was conducted to determine the viability of alternative fuels for Scotland's short-route ferries. The study proved that a key feature of Live-LCA, data generation through simulations, was effective under circumstances where real data is not available.

Unlike Live-LCA, Real-Time LCA (RT-LCA) was designed to be applied to case studies where real-time data is accessible. The real-time data was transmitted through a digital platform developed by LAB021, a Korean ship digital solution provider. The format of outcomes, as real-time observation, was shown to be highly appreciable, while possibly encouraging ship operators to take immediate action to reduce lifecycle emissions if they are plotted too high.

Overall, a key novelty of this thesis is the introduction of Dynamic LCA, which has been proven effective in resolving the fundamental limitations of conventional LCA. Key findings through a series of demonstrative works via case studies are also believed to make a sound contribution to the maritime industry while providing valuable insights into maritime decarbonisation in a holistic way. Lastly, Dynamic LCA can be a new standardised LCA method, challenging rules and policymakers for future regulatory frameworks.

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The goal that started my thesis was to conduct research that could contribute to the shipping sector in the environmental aspect. This idea was inspired by many existing researchers, not just me. I hope that my research will also have a positive impact on future researchers, and I hope that my knowledge and passion will help readers of this dissertation and future PhD applicants.

PUBLICATIONS

IMO documents

- MEPC 80/INF.XX: A Framework for evaluating the life cycle GHG emissions of marine fuels in countries reliant on imported energy through maritime transportation: a case study.

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GLOSSARY

AC	Alternating Current
AFI	Alternative Fuel Infrastructure
AMP	Alternative Maritime Power
AP	Acidification Potential
BDN	Bunker Delivery Note
CF	Carbon Footprint
CH_4	Methane
CI	Cold-ironing
CII	Carbon Intensity Indicator
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2 eq.	Carbon Dioxide equivalent
COC	Confirmation of Compliance
COP	Conference of Parties
DC	Direct Current
DCS	Data Collection System
DP	Dynamic Positioning
ECA	Emission Control Area
EEA	European Economic Area
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EEXI	Energy Efficiency Existing Ship Index
EP	Eutrophication Potential
EPL	Engine Power Limitation
EPS	Electric Propulsion Ship
ETD	Energy Taxation Directive
ETS	Emissions Trading System
ESS	Energy Storage System

GHG	Greenhouse gases
GT	Gross Tonnage
GWP	Global Warming Potential
HSFO	Heavy Sulphur Fuel Oil
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
IEEC	International Energy Efficiency Certificate
IGC Code	International Code for the Construction and Equipment of Ships carring Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ships using Gases or other Low-flashpoint Fuels
IMO	International Maritime Organization
ISO	International Organization of Standardisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LSFO	Low Sulphur Fuel Oil
MARPOL	The International Convention for the Prevention of Pollution from Ships
MCFC	Molten Carbonate Fuel Cell
MEPC	Marine Environment Protection Committee
MGO	Marine gas oil
MLC	Multilevel Converter
MPPT	Maximum Power Point Tracking
MRV	Monitoring, Reporting, and Verification
N_2O	Nitrous oxide
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen Oxides
ODS	Ozone Depleting Substances

PEMFC	Proton-Exchange Membrane Fuel Cell
PM	Particulate Matters
POCP	Photochemical Ozone Creation Potential
PV	Photovoltaic
REPA	Resource and Environmental Profile Analysis
RO	Recognized Organization
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific Fuel Oil Consumption
SO_2 eq.	Sulphur Dioxide equivalent
SO_x	Sulphur Oxides
SOC	State of Charge
SOFC	Solid Oxide Fuel Cell
TtW	Tank-to-Wake
UNFCCC	United Nations Framework Convention on Climate Change
WtT	Well-to-Tank
WtW	Well-to-Wake

1. INTRODUCTION

1.1. Overview

Since 1750, energy use has remarkably augmented as a result of human activities such as rapid technological growth and industrialisation (Intergovernmental Panel On Climate Change, 2007). However, up to now, more than 80% of the energy consumed worldwide is fossil fuels (International Energy Agency (IEA), 2020a). Accordingly, the use of fossil fuels has been continuously increasing, and the global atmospheric concentration of anthropogenic greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) generated by the use of these fuels has notably increased (Acar and Dincer, 2019).

The GHG generated in this way accelerated the global temperature rise, and the global average temperature rise caused climate change such as various natural disasters and continuous sea-level rise. Such climate change has become an inherently global issue, and active responses to solve it have become a core task of mankind that cannot be delayed any longer.

As a result of these environmental impacts, awareness and interest in protecting the environment have greatly increased. The shipping sector is no exception to this global trend.

Worldwide trade has increased dramatically during the last centuries, paralleling the continuous growth of global GDP, as illustrated in Figure 1-1 (a) and (b) (Ortiz-Ospina et al., 2018, The World Bank, 2021). Given that the waterborne transportation accounts for approximately 90% of worldwide trade (Mitchell and Gyanchandani, 2022, Guo et al., 2023, Singh et al., 2012, International Chamber of Shipping, 2014, Scott, 2014, Sustainable Shipping Initiative, 2011), the number and size of marine vessels have also significantly grown during the same period of time (see Figure 1-1 (c) and Figure 1 (d)) (United Nation Conference on Trade and Development (UNCTAD), 2020, Ortiz-Ospina et al., 2018). As a result, shipping has become one of the major sectors contributing to climate change, and a high emitter of SO_x and NO_x, about 14% of global emissions (Bullock et al., 2022, Kontovas, 2020, Micco and Pérez, 2001). 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 (International Maritime Organization, 2014, International Maritime Organization, 2020).

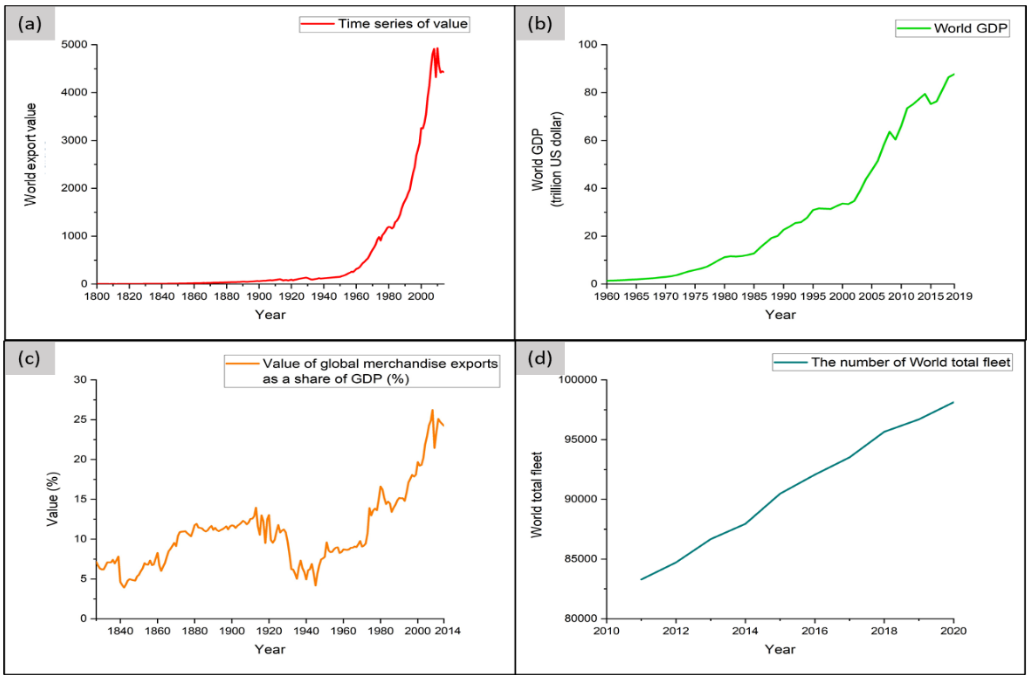


Figure 1-1. Various graphs; (a) World exports at constant prices, relative to 1913 (world export volumes indexed at 1913=100), (b) World GDP, (c) Ratio of global trade to world GDP, (d) World total fleets.

Not only the increase in concern about environmental impacts, but also interest in quality of life is encouraging changes in awareness of environmental issues. As the economy develops and life becomes more affluent, interest in quality of life has increased, and health is a very important factor in determining the quality of life (Ivinson, 2002, Asadi-Lari et al., 2004). Since air pollutants emitted from shipping activities can cause various harmful effects or diseases, such as increased mortality, respiratory distress, skin irritation, and cancer (Kampa and Castanas, 2008, Brunekreef and Holgate, 2002, Viana et al., 2014, Shuai et al., 2017), more research is required to reduce pollutants to protect and maintain health.

In fact, this issue is not limited to certain individuals or experts. At the World Economic Forum, the top global risks were identified in terms of likelihood and impact. Extreme weather, Climate action failure, Human environmental damage, Infectious diseases, and Biodiversity loss were selected as the top global risks by likelihood, while Infectious diseases, Climate action failure, Weapons of mass destruction, Biodiversity loss, and Natural resource crises were identified as the top global risks by impact (McLennan, 2021). As such, environmental issues are being discussed as the most important topic even in global economic issues to the extent that world economic leaders recently selected 7 out of 10 most important global issues as environmental issues.

1.2. Regulations and Issues about Environment in the maritime sector

To solve these problems and as a part of the response, governments and other organisations have made various efforts to reduce pollutant emissions and prevent global warming through global emission commitments such as the Kyoto Protocol and the Paris Agreement. At the 2015 United Nations Climate Change Conference which is the 21st Conference of Parties (COP21, Paris) in 2015, the 'Paris Agreement' was adopted to set and implement gas emission targets. In its content, the global average temperature should not rise above 2℃ compared to pre-industrial levels, and finally, all countries set their own greenhouse gas emissions by aiming for zero net carbon dioxide emissions.

Although the maritime sector was excluded from the Paris Agreement, the International Maritime Organization (IMO) developed and presented a roadmap to support the Paris Agreement. They have 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) (International Maritime Organization, 2021).

Notwithstanding the enterprising stance, the efforts of IMO towards environmental protection have exhibited evident shortcomings. The IMO's focus has been solely on the emissions produced during fuel consumption, thereby neglecting other environmental factors that emerge throughout various stages such as production, transportation, and storage. Consequently, the policy has been viewed as one that disregards these aspects.

1.2.1. SO_x emission control

As shown in Figure 1-2, from 1st January 2020, a new regulation came into force that ships must use fuel oil including less than 0.5% sulphur contents which is LSFO (Low Sulphur Fuel Oil). Prior to this, from 2015, Fuel oil including less than 0.1% sulphur content, ULSFO (Ultra Low Sulphur Fuel Oil), must be used in Emission Control Area (ECA) (International Maritime Organization, 2021).

The sulphur content of fuel oil consumed on ships should not exceed the following limits:

- 4.50 % m/m prior to 1 January 2012
- 3.50 % m/m on and after 1 January 2012
- 0.50 % m/m on and after 1 January 2020 (LSFO)

Within an Emission Control Area (ECA), rules are stricter as followed.

- 1.50 % m/m prior to 1 July 2010
- 1.00 % m/m on and after 1 July 2010
- 0.10 % m/m on and after 1 January 2015 (ULSFO)

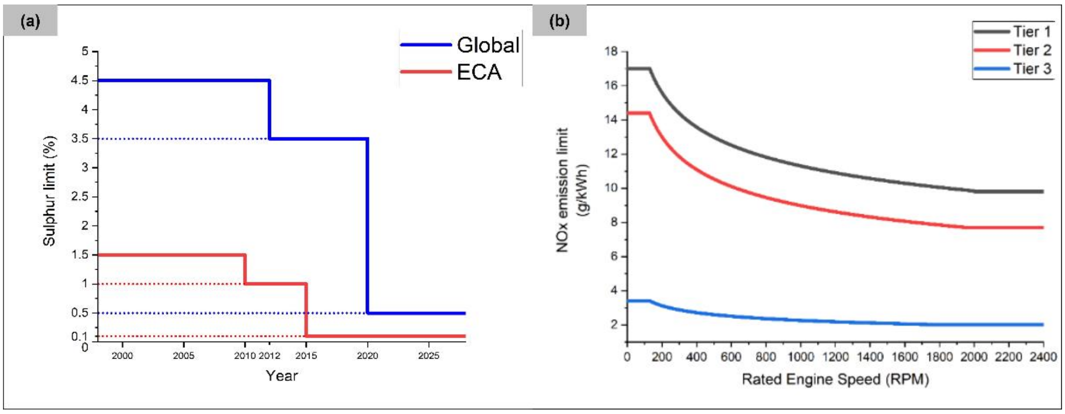


Figure 1-2. Regulation of sulphur content (a) and NO_x emissions (b) in shipping

Consequently, this regulation concentrates solely on mitigating SO_x emissions during the fuel consumption phase by restricting the sulphur content of the fuel employed by vessels.

1.2.2. *NO_x emission control*

For ships built in 2011 or after 2011, Tier 2 regulations are currently being applied, and Tier 3 regulations are being applied only to ships that are sailing in ECA (International Maritime Organization, 2013).

Table 1-1. NO_x emission limits

Tier	Ship construction year (Applicable for this year or later)	NO_X emission limit (g/kWh) n = Rated Engine Speed (RPM)		
		n < 130	n = 130 ~ 1999	n ≥ 2000
I	2000	17.0	$45 \times n^{-0.2}$	9.8
II	2011	14.4	$44 \times n^{-0.23}$	7.7
III	2016* 2021**	3.4	$9 \times n^{-0.2}$	2.0

* ECA in the North America or the US Caribbean
** ECA in the Baltic Sea or the North Sea

Similar to Section 1.2.1, this is an endeavour to mitigate SO_x emissions from fuel consumption without taking into account other stages.

1.2.3. Initial IMO GHG Strategy

The initial strategy of GHG reduction adopted by the IMO in 2018 solidified the existing goal of reducing and phasing out GHG emissions from the maritime sector. This initial strategy emphasised that technological innovation and the introduction of alternative fuels and/or energy sources are essential for international shipping (International Maritime Organization, 2018).

The three levels of ambition for GHG reduction among the initial strategies are as follows (Rutherford and Comer, 2018).

1) Reduction of carbon intensity through the additional implementation of the Energy Efficiency Design Index (EEDI) targeting newly built ships
    - Review for the aim of strengthening the energy efficiency design requirements of ships by appropriately determining and applying the improvement rate at each stage by ship type
2) Reduced carbon intensity of international shipping
    - Efforts to reduce the average CO_2 emission per transport work in international shipping by at least 40% by 2030 and 70% by 2050, compared to 2008 shown in Figure 1-3
3) Peak and decline GHG emissions from international shipping
    - Reach the peak of GHG emissions pronto from international shipping and reduce by at least 50% of the total annual GHG emissions by 2050 compared to 2008

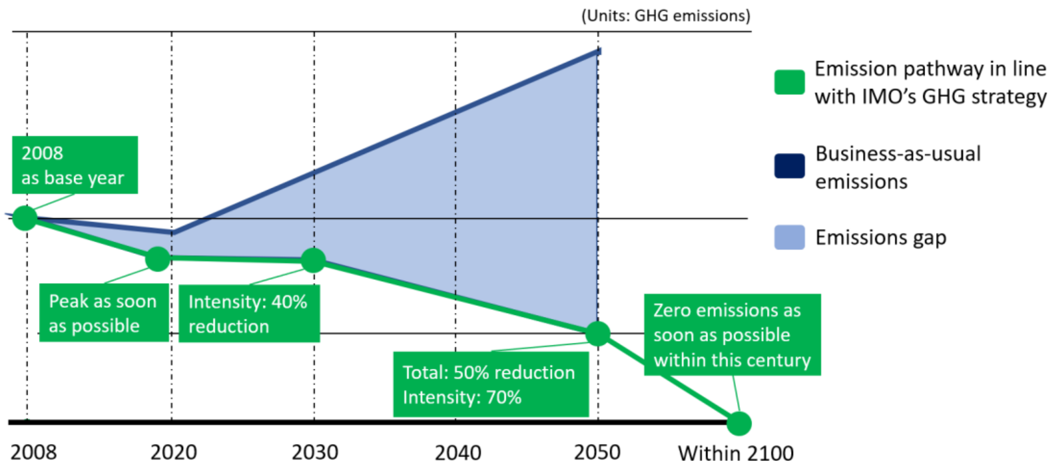
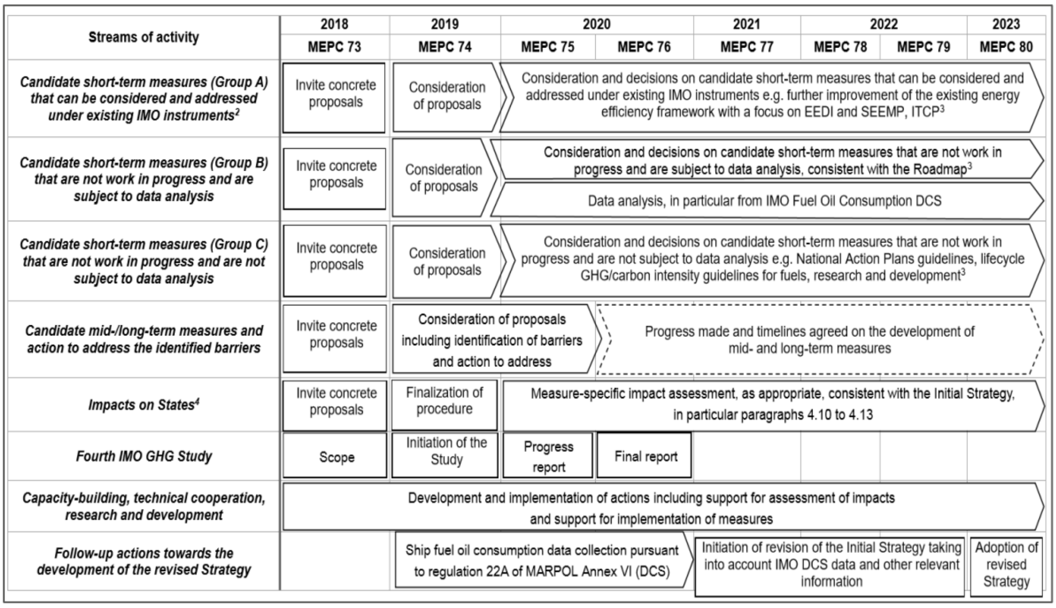


Figure 1-3. IMO strategy for major reduction in GHG emissions from shipping (DNV GL, 2018)

The Initial IMO GHG strategy introduced the concept of lifecycle in the shipping sector, which is significant in addition to the plan for GHG reduction mentioned above. In MEPC 73, to improve the environment, the Initial IMO GHG Strategy sets a clear goal of developing robust life cycle GHG/carbon intensity guidelines for all types of fuels by 2023, with a focus on the lifecycle as shown in Figure 1-4. This has created an opportunity to review the feasibility of utilising environmentally sound methods from upstream to downstream of fuels for the shipping industry not only from the user perspective in the future.

As a detailed process for this, ISWG-GHG 9 initiated a comprehensive procedure to develop LCA guidelines for lifecycle GHG intensity of marine fuels. They have recognised the need to develop a procedure that includes decisive and objective criteria for determining the emission values applicable to a specific situation, and discussions on this topic have taken place.

Following further discussions, MEPC 78 established a Correspondence Group on marine fuel lifecycle GHG analysis with the responsibility for developing draft LCA guidelines. This group is tasked with identifying initial fuel production pathways and feedstocks, and developing methodologies to calculate total GHG emission values including upstream and downstream. Additionally, the group needs to establish a procedure to continuously review the issue of fuel sustainability standards and set emission values.



Streams of activity	2018	2019	2020		2021	2022		2023
	MEPC 73	MEPC 74	MEPC 75	MEPC 76	MEPC 77	MEPC 78	MEPC 79	MEPC 80
Candidate short-term measures (Group A) that can be considered and addressed under existing IMO instruments[2]	Invite concrete proposals	Consideration of proposals	Consideration and decisions on candidate short-term measures that can be considered and addressed under existing IMO instruments e.g. further improvement of the existing energy efficiency framework with a focus on EEDI and SEEMP, ITCP[3]					
Candidate short-term measures (Group B) that are not work in progress and are subject to data analysis	Invite concrete proposals	Consideration of proposals	Consideration and decisions on candidate short-term measures that are not work in progress and are subject to data analysis, consistent with the Roadmap[3] Data analysis, in particular from IMO Fuel Oil Consumption DCS					
Candidate short-term measures (Group C) that are not work in progress and are not subject to data analysis	Invite concrete proposals	Consideration of proposals	Consideration and decisions on candidate short-term measures that are not work in progress and are not subject to data analysis e.g. National Action Plans guidelines, lifecycle GHG/carbon intensity guidelines for fuels, research and development[3]					
Candidate mid-/long-term measures and action to address the identified barriers	Invite concrete proposals	Consideration of proposals including identification of barriers and action to address		Progress made and timelines agreed on the development of mid- and long-term measures				
Impacts on States[4]	Invite concrete proposals	Finalization of procedure	Measure-specific impact assessment, as appropriate, consistent with the Initial Strategy, in particular paragraphs 4.10 to 4.13					
Fourth IMO GHG Study	Scope	Initiation of the Study	Progress report	Final report				
Capacity-building, technical cooperation, research and development	Development and implementation of actions including support for assessment of impacts and support for implementation of measures							
Follow-up actions towards the development of the revised Strategy		Ship fuel oil consumption data collection pursuant to regulation 22A of MARPOL Annex VI (DCS)			Initiation of revision of the Initial Strategy taking into account IMO DCS data and other relevant information			Adoption of revised Strategy

Figure 1-4. Initial IMO Strategy on reduction of GHG emissions (IMO, 2018)

1.2.4. MEPC 76

To achieve the initial IMO GHG strategy, various goals were set, and as a short-term measure, the International Convention for the Prevention of Marine Pollution from ships (MARPOL) Annex 6 amendment was approved at MEPC 75. Subsequently, at MEPC 76 held in June 2021, the amendment to MARPOL Annex 6 including technical guidelines was finally adopted.

The adoption of technological and operational measures to reduce the carbon intensity of international transport from 2023 is a key aspect in MEPC 76, and accordingly, the following measures are highlighted: EEXI, CII, and the enhanced SEEMP.

These regulations represent a new set of requirements that promote change by mandating both operational and technical improvements to existing processes. Specifically, they require that calculations be performed for energy efficiency and carbon intensity in accordance with emissions targets. This is expected to be a significant step in the decarbonisation journey of the maritime industry. While the EEXI has the disadvantage of performing measurements only once during ship construction, the CII performs calculations on an annual basis to ensure compliance with regulations that are continuously strengthened every year. However, despite the importance of these regulations in advancing decarbonisation, they do not address the major drawback of focusing solely on the fuel use side of the calculations.

(a) Energy Efficiency eXisting ship Index (EEXI)

As one of the revised MARPOL Annex 6, EEXI is a regulation corresponding to technical measures. This regulation applies to ships engaged in international voyages of 400 gross tonnage (GT) or more to reduce greenhouse gas emissions, and is implemented from January 1, 2023. Vessels can operate only when the International Energy Efficiency Certificate (IEEC) is issued, which is proof that EEXI is satisfied (DNV GL, 2020).

The Engine Power Limitation (EPL) is being considered as one option to respond to EEXI regulations.

(b) Carbon Intensity Indicator (CII)

CII, an operational approach that is applied from January 1, 2023, is a regulation to measure how efficiently ships transport goods or passengers, and is applied to ships engaged in international voyages of 5,000 GT or more. It is calculated based on the actual annual fuel consumption and operating distance of the ship, and annual grades from A to E are given according to Attained CII compared to Required CII. In addition, in order to continuously reduce emissions, the Required CII value is planned to be lowered annually, and accordingly, the rating thresholds will become increasingly stringent (DNV, 2021). Therefore, in order to maintain the same rating, it is necessary to identify and implement measures to constantly improve the operational efficiency of ships.

Improvement of CII grade is also expected through the implementation of EPL to satisfy EEXI regulations.

(c) *Ship Energy Efficiency Management Plan (SEEMP)* (International Maritime Organization, 2016, Lloyd's Register, 2021)

i) Part I

According to MARPOL Annex VI, ships of 400 GT or more engaged in international voyages must maintain a copy of the SEEMP Part I on board from January 1, 2013.

ii) Part II

From 2019, ships of 5,000 gross tonnage and above engaged in international voyages must collect fuel oil consumption data, based on the amendments to MARPOL Annex VI adopted in 2016. The collected data should be reported to the Administration or Recognized Organization (RO), and the data collection method and reporting procedure should be specified (IMO Data Collection System, IMO DCS). The Confirmation of Compliance (CoC), which is issued after approval by the Administration or RO, must be kept on board the ship.

iii) Part III

Additional modifications to MARPOL Annex VI were adopted at MEPC 76. It describes SEEMP Part III, which includes CII in addition to the existing SEEMP Part I and Part II, implemented from 1 January 2023. The content of it is, vessels subject to CII should develop 'CII calculation method', 'Required CII value for the next 3 years', 'Implementation plans to achieve Required CII' and 'Self-evaluation and corrective action procedures'.

1.2.5. United Nations Climate Change Conference

The 26th Conference of Parties (COP26) to the United Nations Framework Convention on Climate Change (UNFCCC) in Glasgow, United Kingdom, was held to recognise the urgency of climate change and to commit to a lasting and new framework for climate policy and other tangible progress (Hunter et al., 2021). The Clydebank Declaration, defined in COP26, was adopted to achieve the ambitious goal of net-zero GHGs in the shipping sector by 2050, starting with emission-cutting in 2023. This declaration set a much higher target than the IMO's current reduction target of 50% reduction of greenhouse gases by 2050 compared to 2008. In this respect, this declaration is evaluated as a positive move that urges the shipping industry to further contribute for a low-carbon future, and at the same time, that calls for a lot of effort. In addition, the declaration announced that at least six Green Corridors, zero emission maritime routes, would be developed by 2025 as one of the COP26 agreements (Pham et al., 2022, Tinh et al.).

However, all vessels passing through the Green Corridor have no obligation to zero emissions or create and to participate in partnerships between them to reduce emissions. As a result, even though international ports are making great efforts to realise the Clyde Bank Declaration, the reality is that the level of participation and activation of the international community has not yet reached the expected level.

1.3. Toward Net-zero

1.3.1. Net-zero Initiative

(a) United Kingdom

The UK played a crucial supporter in advocating the initial strategy resolution aimed at reducing greenhouse gas emissions from the International Maritime Organization (IMO) to safeguard the environment. In line with this, they clearly articulated their commitment to a 50% reduction in GHG emissions from the shipping sector by 2050 compared to the level of 2008. As a result of this effort, the Maritime 2050 report was released in January 2019, outlining a forward-looking strategic vision for the shipping industry that emphasises sustainability and ecological responsibility (Department for Transport of the UK government, 2019).

The UK government has implemented measures to realise the goals set out in the Maritime 2050 report, including increased support for the transition to environmentally friendly ships. To this end, a government-led shipping office called the UK Shipping Office for Reducing Emissions (UK SHORE) was established. This new initiative is intended to facilitate and promote the adoption of sustainable shipping practices in the UK shipping industry (Daniel and Lee, 2022).

The UK government is committed to achieving net zero greenhouse gas emissions in shipping through the implementation of the UK SHORE, which involves comprehensive research and development activities in collaboration with industry, including the Clean Maritime Demonstration Competition (CMDC), as well as promoting the development of industrial facilities and infrastructure. The strategy encompasses the development of a diverse range of green fuels and technologies, such as electrical energy, hydrogen and ammonia. These activities are expected to serve as a significant catalyst for the British shipping industry's attainment of net-zero emissions, as well as contribute to the clean maritime sector.

(b) European Union

The European Union has announced its commitment to adopting the 'Fit for 55' package and pledging to reduce greenhouse gas emissions by at least 55%

(relative to 1990 levels) by 2030 from a life cycle perspective. Moreover, they also have committed to achieving climate neutrality by 2050 through the revision of the EU Green Deal, well known as European climate law (de las Heras, 2022). Achieving climate neutrality will require a 90% reduction in transportation emissions, and this will require expanding efforts to improve the operational efficiencies of transportation and increase the proportion of consumption of sustainably produced renewable energy sources and low-carbon fuels (European Commission, 2021).

As an action plan for this, the Commission proposed to expand the European Union Emissions Trading System (ETS) to the marine sector and to review the Energy Taxation Directive (ETD). Because even though existing ETS and ETD have the advantage of cost-effectively achieving GHG emission reductions and providing an appropriate price signal to the decisions of each stakeholder, such as operators, investors and consumers, all barriers to solutions to low and zero-emission cannot be addressed adequately. Furthermore, FuelEU Maritime and Alternative Fuel Infrastructure (AFI) are also suggested to achieve the aforementioned goal.

To take active actions to protect the environment through more detailed environmental impact assessment, the well-to-wake (WtW) based evaluation method considering the effects of energy production, transportation, distribution and use, was proposed. This is to reduce the GHG footprint and encourage technologies and production pathways that provide tangible benefits over conventional fuels.

The following items will be considered and discussed as regulations so that these environmentally effective proposals can be efficiently carried out: emission factors based on WtW, applicable emission-free technologies or usage criteria, the rules of conducting simulation, and direct measurements method for emissions. For the shipping sector, it is planned to monitor the WtW emission factors to cover whole related greenhouse gases, broken down into well-to-tank (WtT), tank-to-wake (TtW) and fugitive emissions, for every single type of fuel consumed at berth and at sea.

European Union Emissions Trading System (EU-ETS)

The EU-ETS is a market-based action system designed and operating on the 'Cap and Trade' principle. Within the shipping industry, a cap on the total greenhouse gases emitted from ships is established, and in the event of surpassing the limit, emission rights must be procured via a trading mechanism. Furthermore, the emissions ceiling is gradually reduced on a yearly basis, with the ultimate aim of attaining carbon neutrality across all of Europe's industries (Galdi and Ferrari, 2022).

Energy Taxation Directive (ETD)

The ETD, which stands for Energy Taxation Directive, is a regulatory framework concerning the taxation of energy consumption within the European Economic Area (EEA). This directive aims to promote the use of greener fuels by significantly reducing taxes on such fuels. The expected outcome of this tax reduction is a substantial increase in the adoption of eco-friendly fuels among ships operating within Europe (Kostova, 2022).

FuelEU Maritime

This proposal outlines proactive measures to realise decarbonisation in the shipping industry, as one approach to achieving the 'Fit for 55'. A critical aspect of this proposal is the promotion of sustainable marine fuel utilisation, which require the advancement of environmentally friendly technologies and addressing market barriers (ULLA-MARI, 2022).

This proposal aims to include all ships of 5,000 GT or more that visit European ports, irrespective of their flag state, to achieve the greenhouse gas reduction objective by 2050. The target, which is based on the average GHG intensity from ships in 2020, involves a short-term reduction of 2%

by 2025, with a progressive reduction in emissions leading to a 75% GHG reduction by 2050 as shown in Figure 1-5.

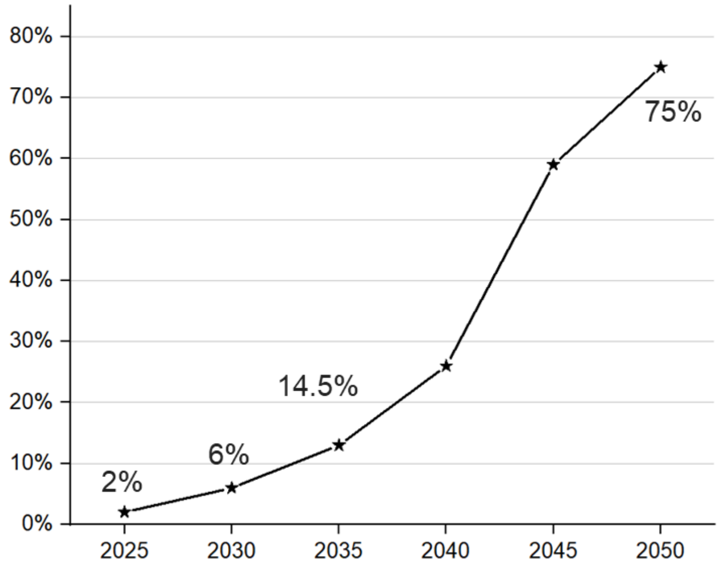


Figure 1-5. Greenhouse gas intensity reduction plan of FuelEU Maritime

To achieve the proposed objective, this proposal recommends specifying the environmental impact of fuels on the Bunker Delivery Note (BDN) and evaluating it from the perspective of the fuel's entire life cycle. It is worth noting that the targets established by FuelEU Maritime do not solely consider fuel usage; instead, they are based on GHG emissions computed using the life cycle of fuels and their associated industrial activities.

In summary, the reduction target of FuelEU Maritime goes beyond shipboard emissions (Tank-to-Wake, TtW) to consider the total greenhouse gas emissions (Well-to-Wake, WtW) generated by various fuels and related engine technologies. Based on life-cycle environmental impact assessments, ships are encouraged to use renewable and low-carbon fuels. Operators are not obligated to use specific technologies to comply with regulations, but they are required to use carbon-free and low-carbon sustainable fuels.

FuelEU Maritime is expected to play a crucial role in the economic aspect of ship operation, similar to the EU-ETS, where penalties are imposed on excess emissions that do not meet the set targets. While the EU-ETS allows for costs/penalties to be avoided by increasing the efficiency of vessel operation, the FuelEU Maritime requires a change in fuel. For instance, if a large bulk carrier emitting about 9,700 t CO2 eq. per year while at sea and about 1,400 t CO2 eq. while at berth continues to use conventional fossil fuels, it may initially incur higher costs under the EU-ETS as shown in Figure 1-6. However, assuming the carbon market is stable, these costs remain constant. Conversely, fines under the FuelEU Maritime will continue to increase, reaching €3.6 million in 2050, about six times the EU ETS. It is worth noting that all calculations of these emissions are performed for the entire process from production to the use of ship fuel using LCA.

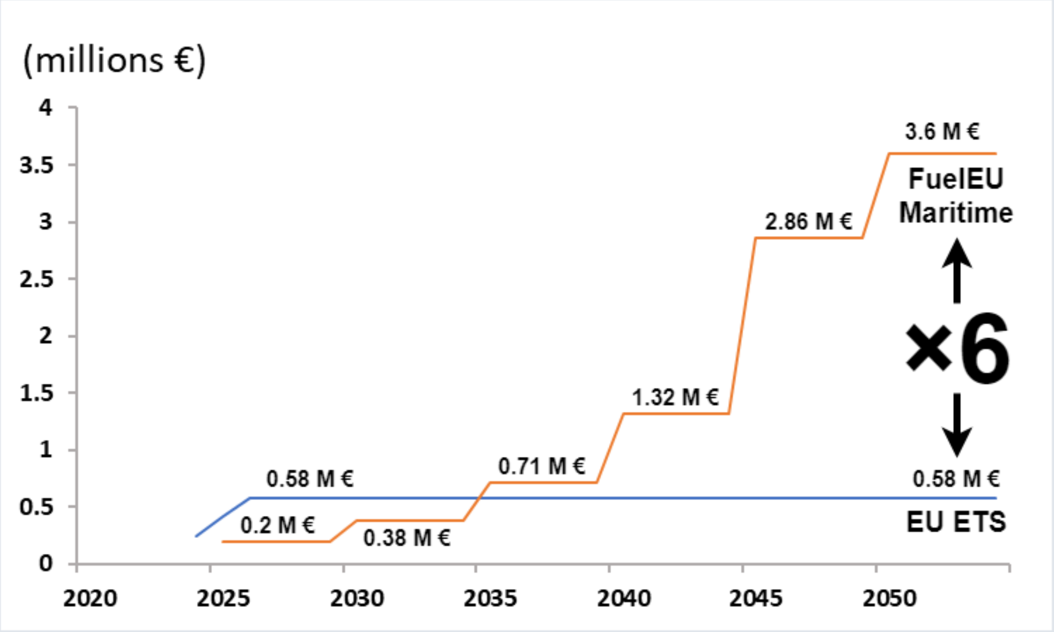


Figure 1-6. Penalty comparison between FuelEU Maritime and EU ETS

Stakeholders who understand the full implications of these environmental regulations can find opportunities to reduce costs. For example, offsetting the penalty of an entire fleet with a few ships with superior performance/environmentality is a possibility. According to Lloyd's Register (2023), if ten conventional fuel ships operate for 5 years (2030-

2034), the potential penalty for FuelEU Maritime is around €277 million. However, if one e-methanol-fuelled ship joins the fleet, the penalty can be waived.

Therefore, based on GHG emission results obtained through LCA, significant cost savings can be achieved through the strategic application of fuel (Solakivi et al., 2022). As a result, the need to emphasise technology development and sustainable energy production capability will continue to be highlighted, and in this process, LCA is expected to become a necessity rather than an option.

Alternative Fuel Infrastructure (AFI)

This proposal is one of the additional steps towards the realisation of FuelEU Maritime. Its provisions comprise the establishment of bunkering infrastructure to facilitate the use of liquefied natural gas (LNG) in the shipping industry, which is a viable and immediate alternative to traditional fossil fuels and can mitigate GHG emissions. Furthermore, the proposal advocates for the deployment of the port power supply to reduce pollution emanating from ports (DINU, 2021).

1.3.2. Discussion on the introduction of Life Cycle Assessment (LCA)

The FuelEU Maritime proposal represents compelling evidence of the European Union's intent to introduce Life Cycle Assessment (LCA) in the shipping industry. Furthermore, the assessment of inland transportation conducted by the European Union offers valuable insights into how the environmental impact assessment and measures proposed by FuelEU Maritime can be evaluated and implemented. In this evaluation, not only the user perspective (TtW) of various fuels, but also the production aspect (WtT) of those were considered (Hill et al., 2020). In other words, the holistic environmental impacts were calculated by considering the overall environmental loads from production to the use of fuels. As such, this method is anticipated to serve as a vital trigger for shifting the focus within the shipping industry from the type of fuel used to the method of fuel production.

Previous EU actions have already had a history of spurring a corresponding IMO response to GHG issues, particularly shortly after the EU adopted the Regulation on Monitoring, Reporting and Verification (MRV) of GHG emissions from vessels, the IMO launched a similar regulation to collect data on global GHG. From these precedents, the European Commission's proposed regulation is highly likely to have an impact on the IMO in the future, and it is expected that the IMO will develop a new LCA guideline to evaluate the well-to-wake perspective of fuels based on this regulation.

1.4. Motivations

The necessity of reducing environmental pollution continues to be a pressing issue, and the severity of climate change caused by pollution is increasing. Numerous activities aimed at mitigating these societal issues and protecting the environment have been implemented. As part of these efforts, various regulations mentioned in section 1.2 have been introduced and implemented. Moreover, to safeguard the environment and comply with regulations, considerable efforts are being devoted to reducing energy consumption and introducing environmentally friendly fuels through various research and activities.

However, despite these efforts, environmental indicators show no signs of improvement, and the severity of environmental pollution continues to escalate. As part of the effort to prevent this phenomenon, the primary motivation of this research is to contribute towards achieving environmental protection in the shipping sector. By identifying the limitations that are not addressed in the current regulations and proposing ways to address the identified weaknesses, this research aims to provide guidance towards further environmental protection and enhanced eco-friendliness.

Furthermore, in the quest to achieve net-zero GHG emissions, countries and organisations are actively engaging in discussions and formulating proposals and regulations. It has become widely acknowledged that reducing GHG emissions, which is considered the leading contributor to climate change, necessitates comprehensive and informed decisions that encompass both the user perspective and production processes. This shift in focus has brought the concept of Life Cycle Assessment (LCA) to the fore, leading to discussions on the suitability of its application in the shipping industry.

Nevertheless, considering the history of early LCA startups, it is notable that they were not initially developed for the shipping industry. Given that the shipping industry operates in a distinctive environment, different from other conventional industries, it is crucial to investigate whether the previously introduced LCA methodology is applicable to the shipping sector. To this end, a rigorous review is deemed and motivated necessarily to validate the methodology's applicability in the maritime sector and provide direction towards safeguarding the environment and transitioning to a GHG-free future.

Developing and providing an environmental assessment tool is crucial to ensure that the new system/fuel required by the shipping sector is a suitable means of protecting the environment from the perspective of the lifecycle. Providing guidelines for selecting a more environmentally friendly system/fuel is no longer optional, but rather a necessity for future generations.

1.5. Outline of the thesis

This thesis consists of 10 chapters and 3 appendices.

Chapter 2 introduces the research aim and objectives with an outline of the thesis to achieve them. In **Chapter 3**, the overviews of the current activities such as studies/applications to increase efficiency and reduce emissions, and the new systems such as electric propulsion and alternative fuels are presented. Additionally, problems and limitations of current activities and systems are identified in this chapter.

A detailed literature review to address the identified issues from Chapter 3 is conducted in **Chapter 4**. In this chapter, existing analysis methods with conventional life cycle assessment methodology are reviewed and analysed to find research gaps and affirm plans to fill them. Based on the results of review and analysis, new methodologies for analysis and evaluation of environmental impacts are proposed in **Chapter 5**. In **Chapters 6 to 8**, case studies are conducted based on the newly proposed methodology. Through this, it is possible to confirm the excellence and effectiveness of the new methodologies compared to the conventional methodology. In addition, case study results prove that the new methodologies must be applied not only to the shipping field but also to the environmental evaluation in general.

The contributions, novelties, limitations of this thesis and recommendations for future work are discussed in **Chapter 9**. Finally, **Chapter 10** summarises and concludes the research.

Appendices A to C provide supplementary information not included in the main text as follows:

- **Appendix A** shows previous research and activities to increase efficiency and reduce emissions.
- **Appendix B** deals with the environmental data for the solar PV system and the data of power from it.
- **Appendix C** presents the functional units with/without fuel transport/storage.

2. RESEARCH AIM AND OBJECTIVES

2.1. Aim and objectives

Based on current circumstances and motivations, the goal and purpose of this research was set. The overall aim of this thesis is to contribute to reducing holistic environmental impacts for marine vessels by introducing a novel lifecycle assessment model, which is the “Dynamic LCA” proposed in this thesis.

In order to achieve the aim, the following objectives are specified:

- Objective 1: To understand the shortcomings of current practices and environmental indicators, and to recognise key challenges.
- Objective 2: To identify the limitations of conventional LCA approaches and their applications to the maritime sector.
- Objective 3: To develop an enhanced LCA methodology suitable for the dynamic behaviour of shipping.
- Objective 4: To demonstrate the effectiveness of the proposed LCA methods through case studies.
- Objective 5: To provide suggestions on proper usage of LCA as a new standard to the marine vessels to achieve clean maritime.

2.2. Outline flow of research and tasks

Several tasks to achieve the aforementioned research aim and objectives are illustrated in Figure 2-1 and described below.

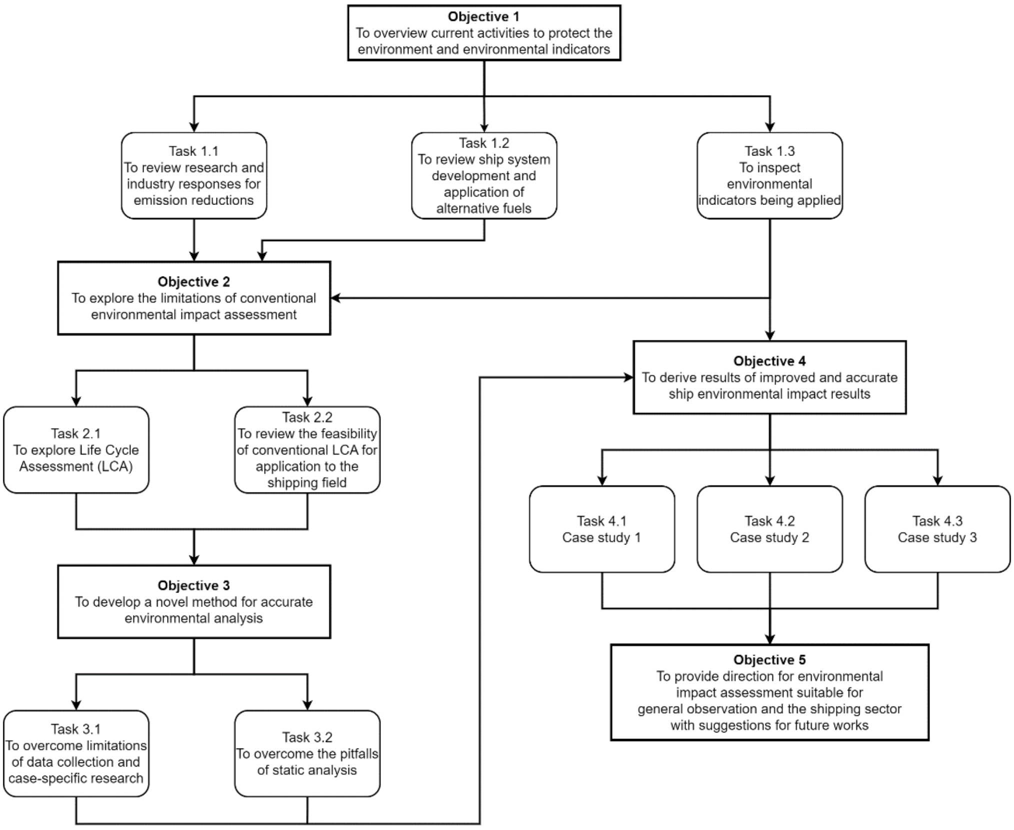


Figure 2-1. Outline flowchart for the research

In this thesis, various environmental protection activities and regulations were organized according to the flow presented in Figure 2-1, and the boundaries of these activities were defined. Based on this, it was explained that the application of Life Cycle Assessment (LCA) in the shipping industry should be actively pursued. However, there are clear limitations to introducing and implementing this concept in shipping, considering the background and methodology of LCA.

To overcome these limitations, a refined LCA methodology called Dynamic LCA was proposed. This enhanced methodology takes into account the unique characteristics and dynamic environment of the shipping industry, allowing for evaluation that reflects real-time changes. Dynamic LCA addresses the limitations of existing data that have been consistently identified as weaknesses in LCA, enabling the derivation of continuous and accurate environmental impacts tailored to the characteristics of ships operating in a dynamic environment.

The effectiveness of the proposed methodology was validated through case studies, demonstrating its ability to derive ship-related environmental impacts in a more reliable and precise manner compared to traditional LCA. Based on these findings, the adoption of Dynamic LCA becomes imperative in order to safeguard the environment in the shipping industry and meet increasingly stringent regulations. Furthermore, this methodology necessitates the revision and supplementation of current regulations to encompass the entire lifecycle of products, from production to consumption and disposal, rather than solely considering the user's perspective.

Moreover, this methodology provides valuable insights into determining which fuels and systems are most effective in achieving the goals of sustainability and net-zero emissions in shipping. Finally, it serves as a guideline for ship operation for stakeholders such as ship operators and owners, offering direction and essential data to policymakers responsible for creating and implementing regulations and policies.

Task 1.1 Overview of responses to protect the environment in academia and industry

Achievement of environmental protection activities was identified by increasing the efficiency of fuels, systems, and devices to satisfy reduce emissions. Simultaneously, the limitations of the activities concerning the holistic environment were also distinctly detected.

Task 1.2 Overview of new systems and application to overcome current issues

The impact of activities to obtain environmental benefits through improvement based on the existing system identified in Task 1.1 is helpful to some extent, but not dramatic. Therefore, the electric propulsion system and new greener fuels that are being studied and considered for introduction for greater environmental advantages are reviewed.

Task 1.3 Review of current environmental indicators

The pitfalls of current maritime environmental indicators along with the existing and new systems based on a limited perspective were clearly confirmed. In addition, the right direction of thinking and decision in the environmental aspect was presented.

Task 2.1 Introduction to Life Cycle Assessment (LCA)

In order to extend the limited perspective in terms of the environment identified in Task 1 to a holistic perspective and identify clear environmental impacts, Life Cycle Assessment was introduced.

Task 2.2 Review of the direction to introduce environmental impact assessment in the shipping sector

The characteristics of LCA, which is widely used for environmental impact assessment, were confirmed, and its suitability for introducing it to the shipping field was reviewed. Most of the fields where LCA has been developed and utilised are onshore sites, and it is characterised by using only existing data for processes based on fixed procedures. By comparing these characteristics with the operating characteristics of shipping, clear defects for the part that could not be covered were identified and supplementary measures were devised.

Task 3.1 Enhanced methodology to evaluate accurate environmental impact

An improved LCA methodology was proposed that compensates for the main disadvantages of conventional LCA; performing limited research based on deficient data which is secured/researched, and impossible to be applied to other cases with different research processes and results.

Task 3.2 Enhanced methodology to apply in dynamic circumstances

Conventional LCA has a decisive drawback in that it has been performed based on static activities. However, ships are based on dynamic activities and are exposed to continuously changing environments, not the same process or sequence. This is the reason why a new methodology that can appropriately reflect this is required, proposed, and applied.

Task 4.1 to 4.3 Case studies

Case studies were conducted by implementing newly developed methodologies in Tasks 3.1 and 3.2. They incorporated the electric propulsion system and diverse fuels reviewed in Task 1.2, resulting in more precise and appropriate environmental impact assessments by taking various factors into account. The findings of case studies have verified the effectiveness of the methodology proposed in this research, thereby establishing the need to transition from the current Life Cycle Assessment (LCA) to the next generation LCA. Moreover, these methodologies can be applied to different types of vessels, facilitating a comprehensive investigation and general observation, and ensuring the rigour of the research and its outcomes.

Task 5 The new paradigm for eco-friendly research in the shipping sector and directions of future studies

This task is deliberated on the effective application of new paradigm environmental impact assessment methodologies, identified in Tasks 4.1 to 4.3, to the maritime sector. Furthermore, an in-depth review of the anticipated effects resulting from the implementation of the methodology was conducted. Subsequently, it provided guidance on the execution of environmental protection activities in the shipping industry, identified the essential activities that should be included, and presented meaningful directions to various stakeholders. Finally, the research concluded by summarising the aspects that necessitate further investigation and future works.

3. LITERATURE REVIEW OF CURRENT APPLICATION

In this Chapter, numerous countermeasures were appraised to meet the aforementioned regulations and rules and achieve reducing emissions toward net zero, such as increasing efficiency, optimal operation, additional devices, applying alternative fuels and new systems/power sources. In addition, current indicators to show emissions from vessels were also reviewed.

This process entailed evaluating the adequacy of the existing emissions reduction efforts and measures towards achieving net-zero emissions, as well as confirming whether the indicators comprehensively reflected the ship's activities. Consequently, this section reviewed the sufficiency of current measures and identified additional factors necessary for effective emission control as shown in Figure 3-1 and Table A-1. Especially, in Table A-1, numerous previous research and activities aimed at increasing efficiency and reducing fuel consumption to meet ever-strengthening regulations are listed in categories ‘Fuel usage & feature’, ‘Engine & System related to fuel’, ‘Environmental effect from fuel’, ‘Environmental issue in the maritime sector’, ‘Devices for environment’, ‘Efficiency for environment’, Alternative fuels’, and ‘LCA study in the maritime sector’ by year which are summarised in Figure 3-1.

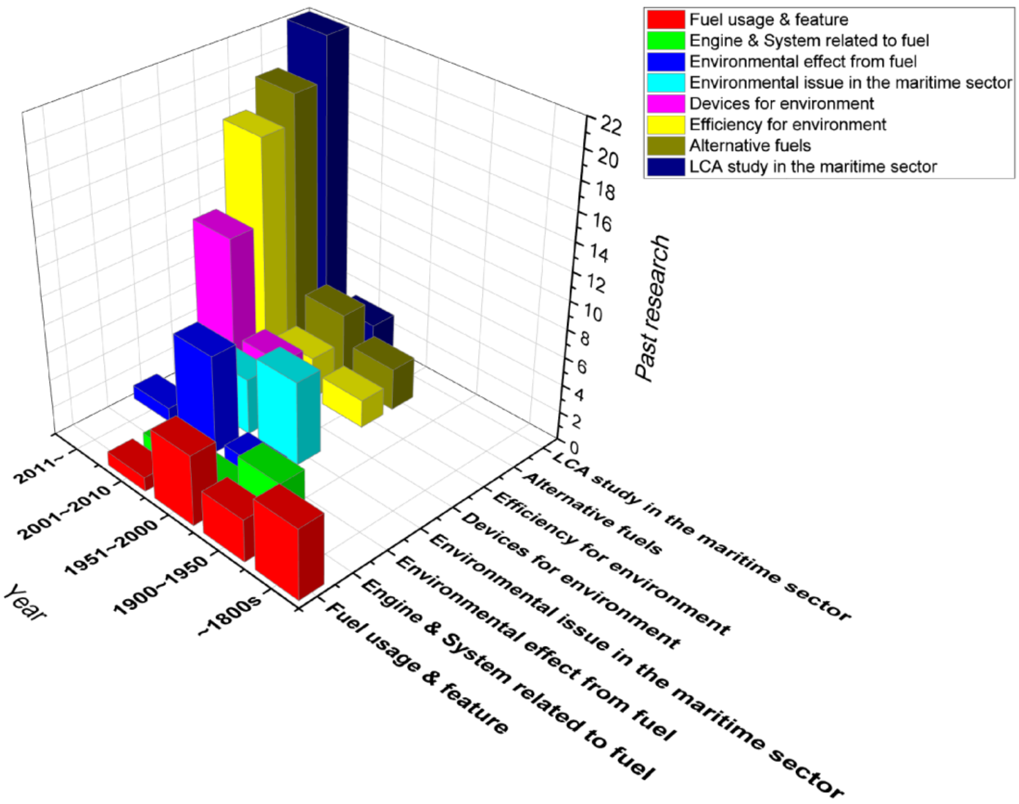


Figure 3-1. Research trends regarding current measures in the maritime sector to achieve net zero and meet regulations

3.1. Past research/technical measures on emission reduction in the marine sector

In order to respond to the GHG emissions regulations mentioned in section 1.2 and 1.3, a variety of technical and operational measures have been introduced, and the contents are summarised in the categories ‘Devices for environment’ and ‘Efficiency for environment’ in Table A-1.

Several studies have explored novel technologies, including slow steaming, hull cleaning, heat recovery systems, and shaft generators, to improve the efficiency of ships and reduce energy consumption. Additionally, proposals for efficient fuel use have been put forward to curtail the amount of energy required for ship operation. These research and development efforts have resulted in a marked reduction in fuel consumption during operation (i.e., use) of ships. However, these activities have primarily focused on reducing fuel consumption during ship operation and only consider the user perspective (TtW).

3.2. New system development and application

The activities listed in section 3.1 are measures to install additional devices or enhance efficiency using existing technologies or systems that can attain certain targets, but do not have large emission reductions to achieve the target of GHG emissions. However, to meet increasingly stringent regulations and reach net zero, more robust research and measures are needed. The activities presented in this section are anticipated to be game-changers that can accomplish net-zero emissions in the future.

3.2.1. Electric propulsion ship

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 (DNV GL, 2019a).

There are three types of electric propulsion system (Karimi et al., 2020b);

1) Diesel-electric system: electricity generated by diesel generators run propulsion motors.

2) Hybrid system: the electric energy used by propulsion motors is produced and supplied by the diesel generator or the energy stored in the battery is used.

3) Fully battery system: the electric energy used on the ship is only supplied by the batteries.

As recognised green maritime solutions (Vahabzad et al., 2020, DNV GL, 2018), those ships are believed to be able to respond to the current demands of maritime environmental protection (Kanellos et al., 2016, Lee et al., 2014, Yang et al., 2020) in addition to various benefits as summarised: higher energy efficiency (Hansen and Wendt, 2015), optimisation of engine room arrangement (Pestanam, 2014, Chai et al., 2018) with less volume and weight (Zahedi et al., 2014), lower operation and maintenance costs (Doorduin et al., 2013), less noise and vibration (Nguyen et al., 2021), high system reliability (Hansen and Wendt, 2015) as well as excellent manoeuvrability (Lee et al., 2014, Sadr and Khanzade, 2013) with remarkable technical advancement (Hansen and Wendt, 2015).

A noteworthy aspect of the electric propulsion system is its ability to achieve considerably high propulsion efficiency across all loads by adjusting the number of generators compared to mechanical propulsion with a single main engine, as illustrated in Figure 3-2 (Hansen and Wendt, 2015). This is because the efficiency of the internal combustion engine increases as the load increases. This feature ensures significant fuel efficiency, which surpasses that of conventional mechanical propulsion methods that are inherently inefficient in the low-load section. Consequently, the electric propulsion system is becoming increasingly recognised as a viable option for protecting the environment.

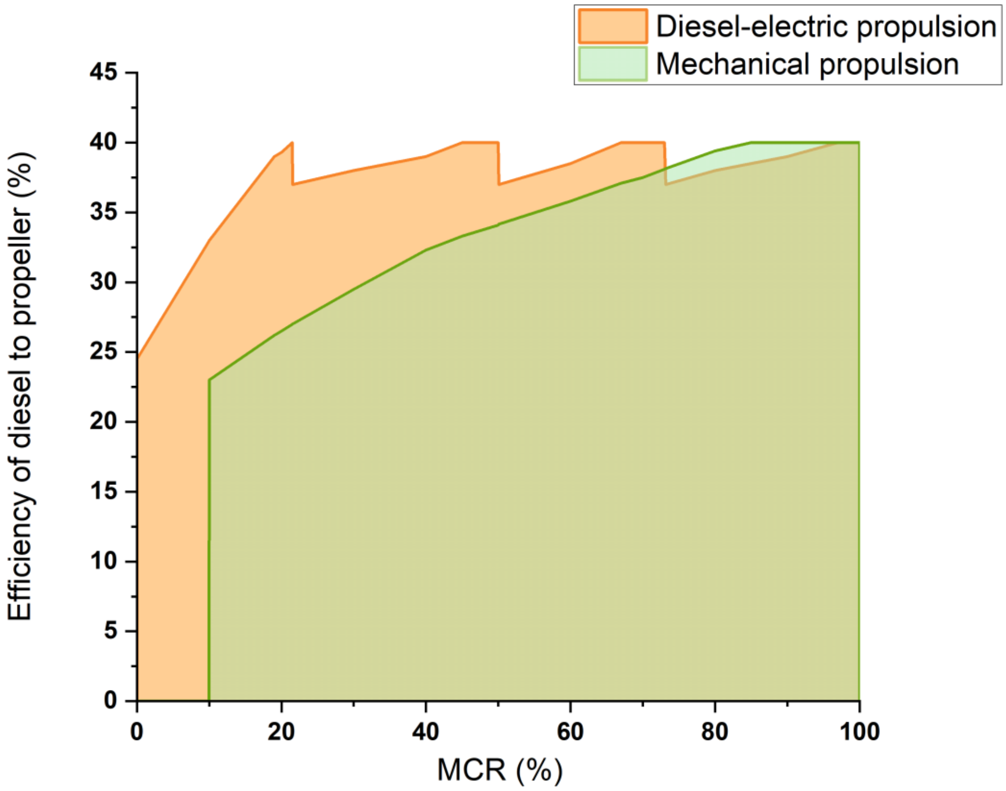


Figure 3-2. Efficiency of ship propulsion depending on the propulsion system

Reflecting these advantages, a study, conducted by Breijs and Amam (2016), analysed a hybrid propulsion system that included batteries and resulted in a fuel savings of 11% when this system was applied to a ferry on sea trials compared to the current mechanical propulsion system. This outcome was achieved by adjusting the battery charging time and implementing a power management system of a hybrid propulsion system.

The electric propulsion system offers various advantages; however, its widespread adoption in the shipping industry is limited by the higher investment costs compared to existing systems. Potential losses arising from the additional conversion stage of the power converter and power quality issues arising from the intensive use of electronic equipment also can be attributable (Geertsma et al., 2017a). Furthermore, installation of a battery necessitates a high-speed charging solution, but inadequate charging infrastructure in many locations exacerbates energy supply and demand vulnerabilities (Karimi et al., 2020a). Battery safety and cost are also commonly cited drawbacks of this technology (Berg and Helldén, 2007, Zahedi et al., 2014).

In terms of electric power system, the AC power distribution system was widely adopted for most electric propulsion ships in the past. 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 (Hansen and Wendt, 2015, Hansen et al., 2011, Pestanam, 2014). The advantages of the DC distribution system over the AC distribution system in the electric propulsion ship can be summarised as below (Hansen and Wendt, 2015, Hansen et al., 2011, Kim et al., 2018).

- 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 as shown in Figure 3-3 (Pestanam, 2014). In the study by Pestanam (2014), DC system can reduce around 13% of fuel consumption when it is applied to Platform Supply Vessel (PSV) with DP operations for 35% of the schedule, steaming for 25%, standby for 15%, and port for 25%.

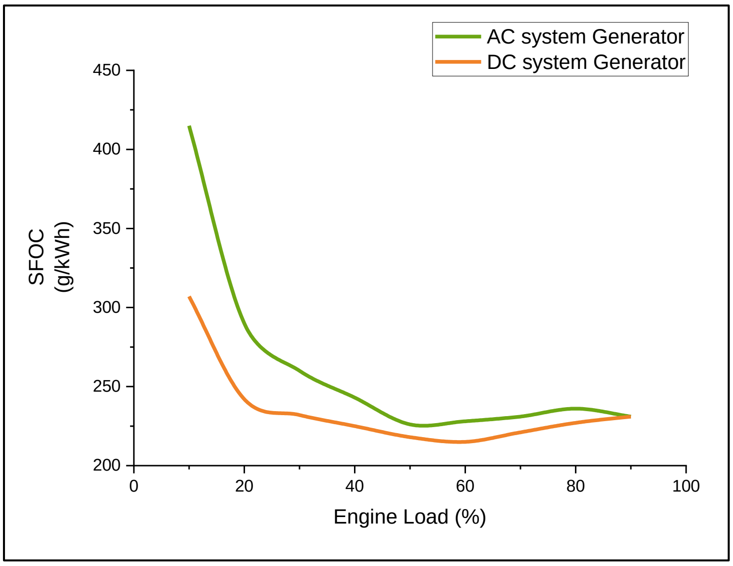


Figure 3-3. SFOC of generator in different current systems

- Fast parallel operation is possible because generator synchronisation is not required.
- 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.
- Reduced maintenance costs due to fewer breakdowns since the engine continues to operate at its optimum operating point.
- 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.
- Unlike AC systems where reactive power is present, DC systems have no problem with reactive power interactions, making it easy to maintain power stability.

The DC system is presently under extensive consideration for employment in electric propulsion ships, given the aforementioned various advantages. In particular, ships that necessitate continuous adjustments in propulsion speed, such as passenger ships, ferries, and military vessels, stand to derive significant energy-saving benefits from the implementation of the DC system (Nguyen et al., 2021).

Notwithstanding the many benefits offered by the DC system, there exist several challenges that demand attention. Firstly, power electronic converters must be utilised to interconnect devices, such as loads and power sources, in a DC system. Moreover, since numerous loads, such as motors, necessitate AC power, the greater the number of such devices, the higher the cost of power conversion (Nguyen et al., 2021). Lastly, the major drawback of the DC system is the protection system. In contrast to AC systems, which are capable of swiftly de-energising and clearing arcs at zero crossings of current in the event of a fault, DC systems lack such crossings. Thus, DC systems require more sophisticated circuit-breaking techniques to be applied (Skjong et al., 2016).

In the name of environmental protection, a lot of policy efforts are being made to convert cars that use existing fuel into electric cars, and accordingly, much public attention is being focused (Burchart-Korol et al., 2020, Wu et al., 2018). In line with this trend, it is true that from the popular and generalised perspective, the electric propulsion ship is also viewed as an eco-friendly ship. On the other hand, there are very few fundamental and holistic studies on whether the electric propulsion ship is truly eco-friendly ships, and in the meantime, technical aspects such as efficiency, control, etc. have been intensively studied in research on the electric propulsion ship.

3.2.2. Auxiliary power system

(a) Battery

Battery is a key energy storage system, and their utilisation is gradually increasing. To charge it, alternative marine power (AMP) from onshore supply the electricity.

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. As shown in Figure 3-4 (Kularatna, 2014), it is clearly indicated that batteries are an excellent energy storage type when considering both power density and energy density. Therefore, it is largely used in a wide variety of industries including marine vessels (Ovrum and Bergh, 2015, Wen et al., 2016). In particular, Li-ion batteries are found excellent in power density (Song et al., 2019, Maheshwari et al., 2020).

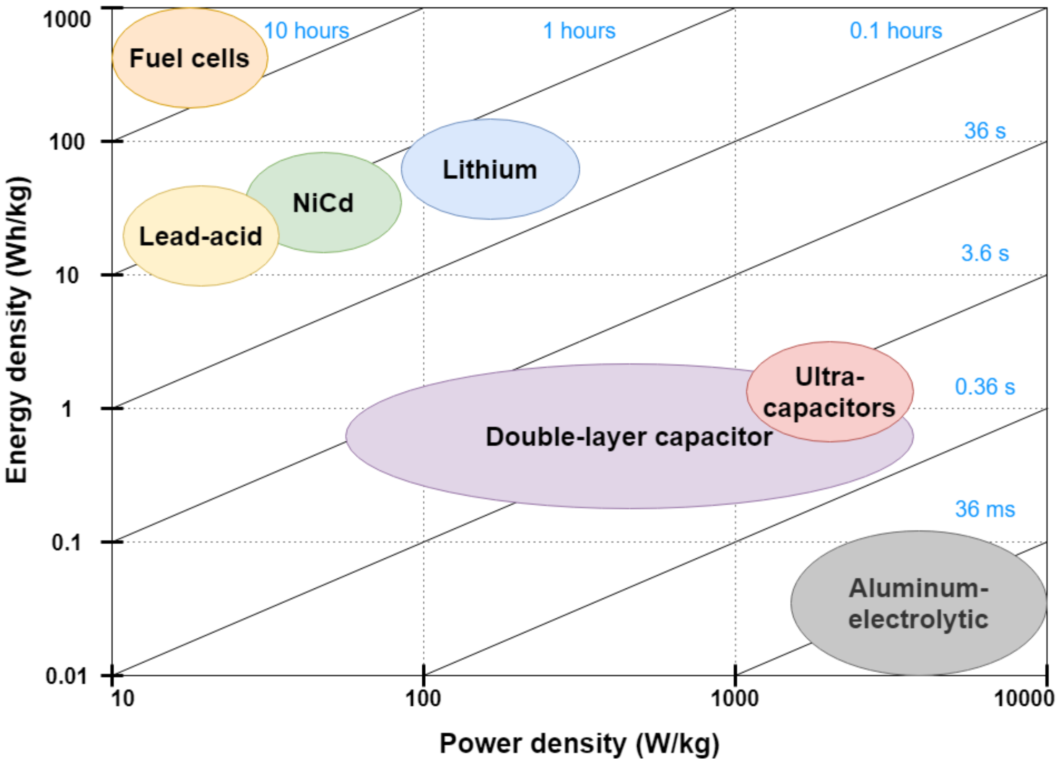


Figure 3-4. Power density and Energy density of energy storages

In addition, (Buchmann, 2017) compares the capacity retention of batteries over the number of operation cycles as shown in Figure 3-5. 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.

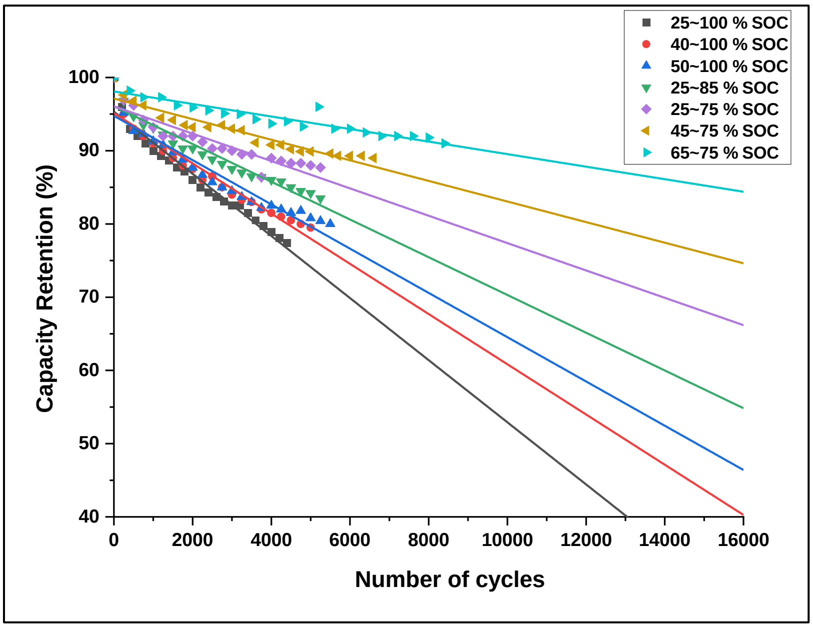


Figure 3-5. Actual capacity loss of battery by charging and discharging and expectation of battery life by extrapolation

The present studies provide the basis for the selection and application of an energy storage system (ESS), which can be utilised with safety and efficiency in shipping. Furthermore, the research findings propose an approach to utilisation that has the potential to conserve more energy and minimise emissions from the user's standpoint.

(b) Solar PV

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 (Wei et al., 2021), optimisation of the residential solar system

(Amabile et al., 2021), and research by Li et al. (2021) to investigate the efficient installation status of solar panels 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 by Schleifer et al. (2021), and a hybrid power generation system including those with diesel generators was also performed by Marqusee et al. (2021). However, through the development of technology and various studies, recent attempts to apply and utilise the solar PV system to ships are continuing.

Solar energy is subject to challenges as power generation is highly dependent on environmental conditions (Li et al., 2020, Wen et al., 2016, Amabile et al., 2021) and it may be difficult to secure enough space for PV systems onboard (Li et al., 2021). 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 by Wei et al. (2021) with a short payback time through fuel savings (ABS, 2017). In addition, compared to other renewable technologies, the weight of solar panels is light and easy to apply (Nguyen and Dong, 2020). 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 (Lee et al., 2013, Nasirudin et al., 2017, Schleifer et al., 2021, Marqusee et al., 2021).

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 (Nuchturee et al., 2020, Kim et al., 2016). Here are some representative examples. Lim et al. (2019) conducted a prediction of electric power consumption on electric propulsion ships to determine the capacity of the generator and propulsion motor. Hansen et al. (2011) studied the onboard DC grid system, and Thantirige et al. (2015) examined multilevel converter (MLC) topologies that are suitable for medium voltage drives. In addition, Hou et al. (2017) contributed to mitigating frequent power fluctuations due to changing propulsion motor load and external factors on electric propulsion ships. In addition, Table A-2 summarises 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.

The PV electric vessel runs on electricity from the onboard PV system, and from the national grid if the PV system is not able to fully meet the required power. The holistic environmental impacts on electricity generation vary greatly depending on primary energy resources, technologies and geographic conditions (Turconi et al., 2013), 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.

(c) Wind

The utilisation of wind technology as a major propulsion for ships persisted until the 19th century, when the steamship emerged. The invention of ships powered by steam engines provided greater flexibility and reliability in transporting cargo and passengers, resulting in the gradual decline in the employment of wind technology in shipping (Harlaftis et al., 2012).

Wind energy is a pollution-free and clean energy source that holds promise in accelerating the decarbonisation of the shipping industry. Recent advancements in research and development, as well as ship application cases, have increased interest in the use of wind technology (Argyros, 2015).

Various wind technologies have been developed as auxiliary propulsion units for ships, such as the following types (Delft and Fraunhofer, 2016, Lu and Ringsberg, 2020).

Flettner Rotor: It generates forward thrust by employing the Magnus effect through the use of electrically powered rotating cylinders that are installed perpendicular to the deck.

Towing kite: After sending a large kite to a high altitude, it uses the thrust generated by wind.

Wingsail: It generates propulsion by creating a lifting effect while reducing the induced drag that slows the vessel, and is similar to an aerofoil that employs aerodynamic force.

Soft sail: It utilises a traditional sail with modern features, rotating the sail itself to obtain optimal lift. DynaRig is the representative type.

Wind turbine: It is a type of turbine installed on the deck of a ship that generates thrust or electricity for propulsion. However, due to the size of the turbine, it is generally challenging to apply it to merchant ships, although it is used in some yachts.

According to recent research, the fuel saving effect of wind power on a ship varies depending on the speed. However, Schlaak et al. (2009) has reported that wind power can result in savings of up to 36%. Furthermore, Chou et al. (2021) has conducted extensive research on various types of wind-powered technologies. The results indicate that the application of these technologies can result in fuel efficiency increases ranging from 0.4% to 60%. Specifically, the Flettner rotor can result in fuel efficiency increases of 0.4% to 50%, towing kites can lead to increases of up to 50%, wing sails can result in increases of 5% to 60%, soft sails can increase between 4.2% and 35%, and wind turbines can result in increases of 1% to 4%.

It is clear that these studies have been conducted with focusing on increasing efficiency and reducing fuel consumption in relation to the TtW perspective regarding fuel use.

3.2.3. Alternative fuels

Since alternative fuels are strongly regarded as a promising solution to abate GHG emissions and mitigate/restrain climate change, introducing alternative fuels to the maritime sector is very crucial, essential and indispensable. Based on the DNV's report as shown in Figure 3-6 (DNV GL, 2019c), it is clearly shown that, by 2020, oil, which accounts for more than 90% of the fuel used in the shipping sector, will gradually be replaced by alternative fuels. However, it is projected that the usage of HFO will persist, and its consumption, which has significantly declined due to stricter regulations, is anticipated to slightly increase in the future due to the development and maturation of Onboard Carbon Capture System (OCCS) technology. In addition, from 2038, alternative fuels are predicted to be used more than oil and the use of greener fuels is expected to increase continuously. A notable aspect is that the overall energy consumption is expected to exhibit a gradual decline until 2050, despite the anticipated growth in shipping activities attributed to increased freight volumes. This is attributed to the projected reduction in energy consumption per tonne-mile by 35% to 40% by 2050, driven by ongoing technological advancements (DNV GL, 2019c).

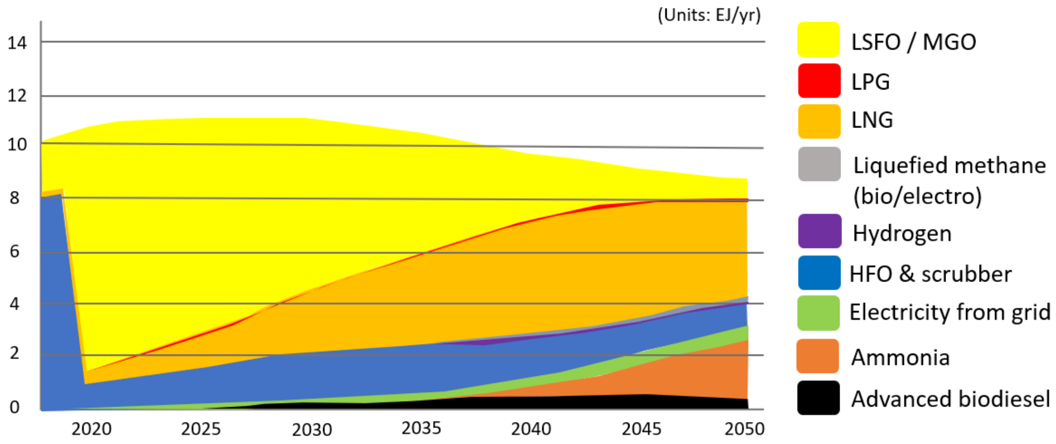


Figure 3-6. Energy use and projected fuel mix 2018–2050 for the simulated IMO ambitions pathway with main focus on design requirements

There has been a lot of research on fuel used in the maritime sector from the past.

As shown in Figure 3-1 and Table A-1, energy-related research in the maritime sector shows a clear trend, which is Environmentality. Until the 1800s, research was carried out simply focusing on how to use fuel (Allen, 1730, Paul, 1865, Richardson, 1865, Clark, 1884, Edwards, 1895), but from the 1900s, it developed into research related to the characteristics of the fuel itself (Blackiston, 1909, Daniels, 1921, D'Eyncourt, 1929, Chung et al., 2000). Research on the use of fuel considering the characteristics of ships and engines (Verhey, 1920, Lucke, 1921, Evans and Brierly, 1928, Beck and Miller, 1944, Shi et al., 2010), the emulsification of fuel oil and etc (Martin, 1951, Harbach and Agosta, 1991, Lin et al., 1995a, Lin et al., 1995b), contributed to the development of the shipping field. But apart from these efforts, the world has faced environmental problems. Accordingly, research on the environment was actively conducted in earnest to obtain answers to global environmental problems such as global warming. Various environmental issues, such as emissions from fuel mainly used in ships (Capaldo et al., 1999, Corbett, 2004, Endresen et al., 2007, Winnes and Fridell, 2009, Dalsøren et al., 2009, Moldanová et al., 2009, Popovicheva et al., 2009, Agrawal et al., 2010, Zhang et al., 2021), as well as emission, policies and environmental regulations in the shipping field (Register, 1990, Carlton et al., 1995, Okamura, 1995, Kütting and Gauci, 1996, Corbett and Fischbeck, 1997, Lawrence and Crutzen, 1999, Endresen et al., 2003, Cofala et al., 2007, Han, 2010), were studied. In addition, abundant research on devices for environmental improvement and methods to increase energy efficiency have also promoted the eco-friendliness of the shipping industry (Stefanopoulou and Smith, 2000, Cooper, 2001, Seif and Tavakoli, 2004, Dimopoulos et al., 2008, Ballou et al., 2008, Gully et al., 2009, Dedes et al., 2010, Geertsma et al., 2017b, Geertsma et al., 2017a, Planakis et al., 2022).

However, in spite of these efforts, it was true that the existing system alone was insufficient to suggest a policy direction to meet continuously tightening environmental regulations or alternatives for environmental improvement. In consequence, interest in alternative fuels rather than conventional fuels has increased.

The fastest alternative fuel that can replace existing oil fuel is LNG. This is because it is appropriate compared to other alternative fuels considering all indicative status, including technological maturity, fuel availability, and rules such as The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) and International Code of Safety for Gas Fueled Ships (IGF Code) (Elgohary et al., 2015), as shown in Figure 3-7. Furthermore, the use of LNG can reduce more than 70% of NOx, 90% of SOx, and 85% of particulate matter (PM) compared to conventional fuels, therefore LNG, which can be immediately applied, is evaluated as a very attractive alternative fuel (Banawan et al., 2010, Sui et al., 2020).

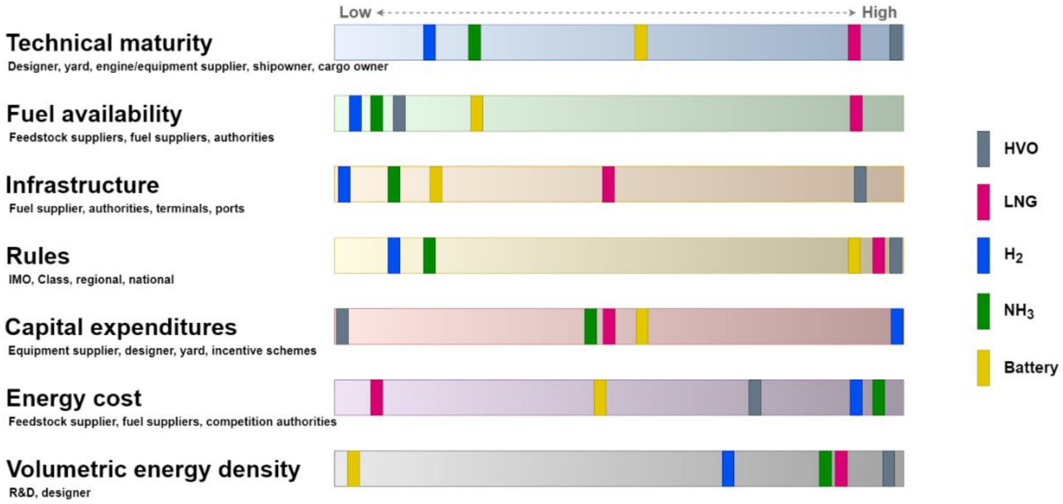


Figure 3-7. Indicative status of alternative fuels (DNV GL, 2018)

However, since LNG, a carbon-based fuel, has only about 10-20% greenhouse gas reduction effect compared to conventional fossil fuels (Arteconi et al., 2010), there is a limit as an alternative fuel that can solve global warming, which is currently the most serious problem. Therefore, such interest has led to research on various alternative fuels such as nuclear, biofuel, and carbon-free fuels including ammonia, hydrogen, and plug-in electricity (Ford, 1977, Khlopkin and Zotov, 1997, Farrell and Glick, 2000, Calfo et al., 2002, McCoy, 2002, Brett, 2008, Banawan et al., 2010, Van et al., 2019, Hansson et al., 2019, Al-Enazi et al., 2021).

On the other hand, ships are involved in a variety of activities that lead to energy supply and demand, consumption and emissions. Therefore, to estimate the overall environmental impact of a given vessel, it is necessary to track and analyse the flows of energy and emissions associated with every single activity at various life stages. However, the research on these various alternative fuels has only focused on fuel use, technical aspects and the simple reduction of emissions when existing fuel is converted to alternative fuels (Brett, 2008, Banawan et al., 2010, Van et al., 2019, Iannaccone et al., 2020, Sui et al., 2020, Sapra et al., 2021, Al-Enazi et al., 2021, Fan et al., 2022).

Despite the considerable variety of studies, research on alternative fuels in the shipping field has limitations in not comprehensively reflecting various ship-related activities aforementioned. Most of the studies showing the difference in emissions according to fuel do not consider the upstream of the fuel, but only the user aspect (Capaldo et al., 1999, Endresen et al., 2007, Winnes and Fridell, 2009, Dalsøren et al., 2009, Moldanová et al., 2009, Zhang et al., 2021). In addition, research on pollutants generated from ships focused only on exhaust gas emissions due to energy consumption (Kütting and Gauci, 1996, Lawrence and Crutzen, 1999, Endresen et al., 2003, Delft et al., 2006). In the case of alternative fuels, despite the fact that the amount of emissions generated from the viewpoint of the life cycle is significantly different according to various production methods, the production stage was not considered in studies by Brett (2008), Van et al. (2019), Sui et al. (2020), and Al-Enazi et al. (2021). Therefore, the holistic study should be introduced to identify the comprehensive aspects including fuel production for alternative fuels.

3.3. Current indicators for measurement of emissions

The IMO has adopted several indicators that are vital in introducing regulations aimed at safeguarding the environment in the international shipping industry. These indicators play a significant role in evaluating the energy efficiency and carbon emissions of ships to measure and improve their environmental performance. By monitoring the energy efficiency and carbon emissions of ships, these indicators have become a fundamental tool in promoting sustainable shipping practices and reducing the environmental impact of the shipping industry.

(a) Energy Efficiency Design Index (EEDI)

It is an indicator to evaluate the energy efficiency of newly built ships which is adopted at MEPC 62 in 2011.

$$EEDI = \frac{\sum P \times C_f \times SFOC}{Capacity \times V_{ref}} \tag{1}$$

Where; P is power of a ship, C_f is the fuel mass to CO_2 mass conversion factor, SFOC is certified Specific Fuel Oil Consumption in g/kWh, Capacity is the deadweight, V_{ref} is ship speed in nautical miles per hour.

Briefly, it can be explained as ‘Total energy consumption / Distance travelled’.

(b) Energy Efficiency Operational Indicator (EEOI)

It is an indicator to evaluate the energy efficiency of in-service ships which is adopted at MEPC 64 in 2013.

$$EEOI = \frac{\sum_j (FC_j \times C_{Fj})}{m_{cargo} \times D} \tag{2}$$

Where; j is fuel type, FC_j is the mass of the consumed fuel j, C_{Fj} is the fuel mass to CO_2 mass conversion factor for fuel j, m_{cargo} is cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships, D is the distance in nautical miles corresponding to the cargo carried or work done.

Briefly, it can be depicted as ‘Total energy consumption / Total distance travelled or transport capacity’.

(c) Energy Efficiency Existing Ship Index (EEXI)

It shows the energy efficiency based on the information on existing ships over 400 GT. It is adopted at MEPC 76 in 2021. EEDI evaluates the energy efficiency of newly built ships based on their design, whereas EEXI evaluates the energy efficiency of existing ships based on their actual performance.

$$EEXI = \frac{\sum P \times C_f \times SFOC}{Capacity \times V_{ref}} \tag{3}$$

Where; P is 75%/83% of the rated installed power (maximum continuous rating, MCR), C_f is the fuel mass to CO_2 mass conversion factor, SFOC is certified Specific Fuel Oil Consumption in g/kWh, Capacity is the deadweight, V_{ref} is ship speed in nautical miles per hour.

Shortly, this indicator can be explained as 'Ship's designed maximum energy efficiency' / 'Current ship's energy efficiency'.

(d) Carbon Intensity Indicator (CII)

It measures and displays the degree of continuous improvement in reducing the carbon footprint of the international shipping industry, adopted at MEPC 76 in 2021.

$$CII = \frac{\sum_j (FC_j \times C_{Fj})}{Capacity \times D} \tag{4}$$

Where; j is fuel type, FC_j is the mass of the consumed fuel j, C_{Fj} is the fuel mass to CO_2 mass conversion factor for fuel j, Capacity is the deadweight, D is the distance in nautical miles corresponding to the cargo carried or work done.

In simple expression, 'CO_2 emissions during operation' / 'Distance travelled or transport capacity'.

Upon reviewing the environmental indicators currently employed in the shipping sector, certain observation has come to light. Specifically, these indicators are calculated based solely on the ship's operational use, without considering the fuel's full life cycle impact. Consequently, while emissions generated during fuel usage are considered, emissions arising from fuel production are absolutely neglected.

3.4. Research gap identification

In this chapter, various efforts to reduce emissions to protect the environment have been explored. As can be clearly seen in Table A-1, previous research in the field of shipping has solely emphasised the user's perspective on the TtW aspect, without providing a comprehensive analysis of the multifarious activities associated with ships from a holistic viewpoint.

To achieve the proper use of the electric propulsion ship and the PV installed ship, the fundamental way to proper use should be answered by determining the correlations of the environmental performance of electric ships and PV 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.

Given that, the past publication as listed in Table A-1 and Table A-2, 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.

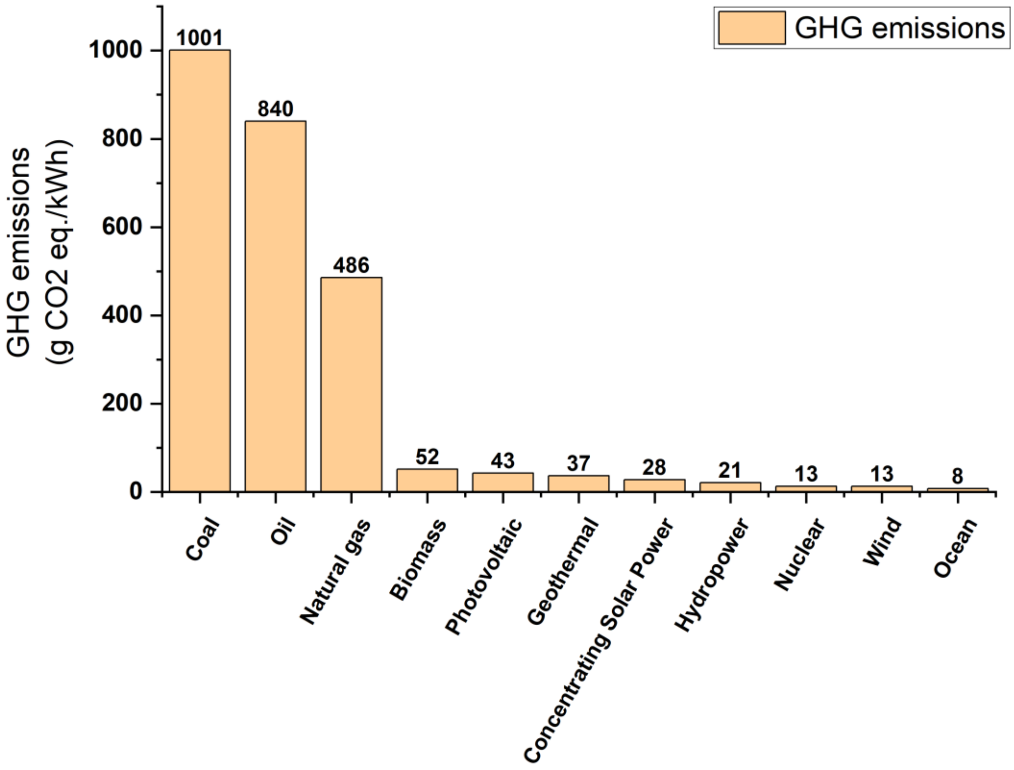


Figure 3-8. Lifecycle GHG emissions factors for electricity

In fact, the environmental impact of electrical energy is subject to substantial variation, based on the type of fuel used during the production stage, as illustrated in Figure 3-8 (National Renewable Energy Lab., 2021), when evaluated through a holistic perspective.

Despite a variety of technical and operational measures and the introduction of electric propulsion ships, it is still neither conceivable to achieve 50% GHG reduction target by 2050 nor to accomplish the net-zero target in the EU. Table A-1 also presents the research on carbon-low or -neutral fuels, suggesting that those alternative fuels can be the only solutions to meet current demands.

Nevertheless, it is true that most of the studies on whether a certain fuel can emit less emissions and protect the environment have been identified only from the user's point of view. Furthermore, the current indicators that measure and evaluate the energy efficiency and emissions of ships, such as EEDI, EEOI, EEXI and CII, can only confirm the consumer side.

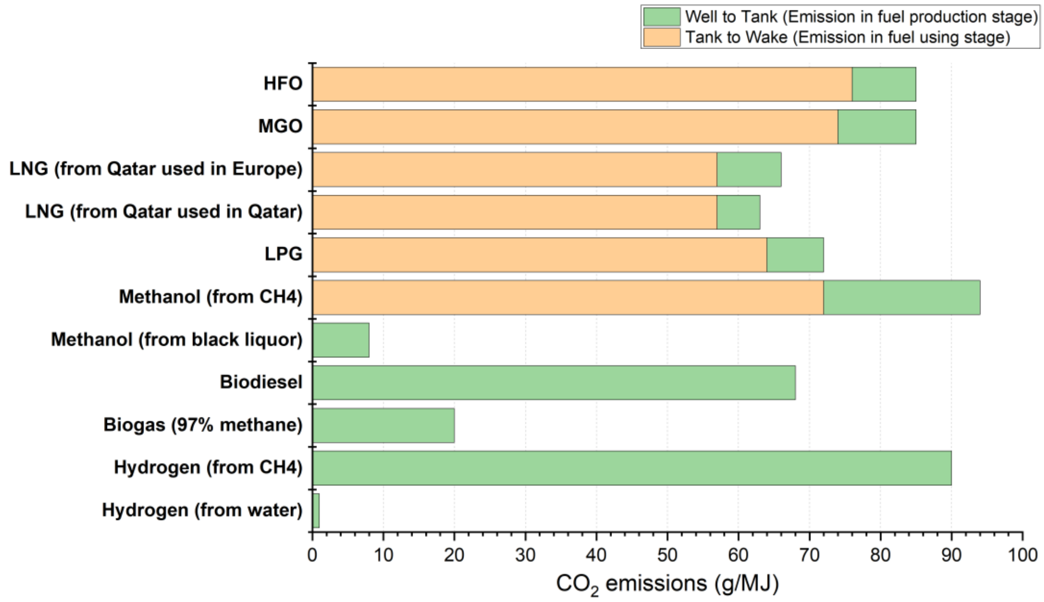


Figure 3-9. CO_2 emissions of alternative fuels in shipping

Contrary to the assertions of numerous studies, cited in Table A-1, that suggest alternative fuels as the optimal method for safeguarding the environment, it is confirmed that greener fuels have significantly different environmental impacts, which are contingent on the production method employed and exhibit a similar trend to electrical energy, as illustrated in Figure 3-9 (DNV GL, 2019b). Furthermore, a holistic perspective reveals that even in the case of hydrogen fuel, which is expected to resolve future environmental issues, the environmental impact is dependent on the production method, and it can be confirmed that more GHG emissions are generated than by highly polluting HFO.

Therefore, this thesis strongly argues that a comprehensive life cycle approach should be adopted to address the full impact of shipping operations on the environment, including upstream emissions from fuel production, transportation, and refining, in addition to downstream emissions from ship usage. Life Cycle Assessment is a methodology that can be an appropriate answer to this need. By adopting a comprehensive approach with LCA, the shipping industry can promote a more sustainable and environmentally-friendly sector.

4. LITERATURE REVIEW OF LIFE CYCLE ASSESSMENT

The purpose of this chapter is to introduce Life Cycle Assessment (LCA) and fill the research gap in order to address the issues identified in Chapter 3. Most studies/activities to improve the environment only focused on the user perspective, even though the impact is not negligible as confirmed in Figure 3-9. LCA complements these problems and makes it possible to more thoroughly check the environmental impact. This chapter focused on identifying deficiencies of current LCA designed to adequately assess environmental impacts and determining whether conventional LCA can be properly applied to the shipping sector. As a result, it was identified and clarified disadvantages and limitations of conventional LCA that need to be overcome and improved to suit the characteristics of the shipping field. Based on identified pitfalls, the enhanced way will be suggested to reflect the dynamic shipping environment. Through this, this chapter is to provide direction to more accurately and reliably capture the environmental impact of the shipping sector from a holistic perspective.

4.1. LCA history

The Life Cycle Assessment (LCA) is a contemporary term referring to a holistic environmental management tool that was defined in the 1980s and 1990s. Prior to this, several terms/concepts, including Resource and Environmental Profile Analysis (REPA) or Ecobalance, were employed to determine environmental impact. However, at present, the term LCA is widely used to represent environmental assessment. The concept of environmental assessment has progressed from a simple analysis of energy use to a comprehensive evaluation of environmental load and impact. Recently, LCA has evolved into a technique that addresses environmental, resource, and energy issues comprehensively, and it is currently expanding into research that considers sustainability (Guinée, 2016, Valdivia et al., 2021, Finkbeiner et al., 2010).

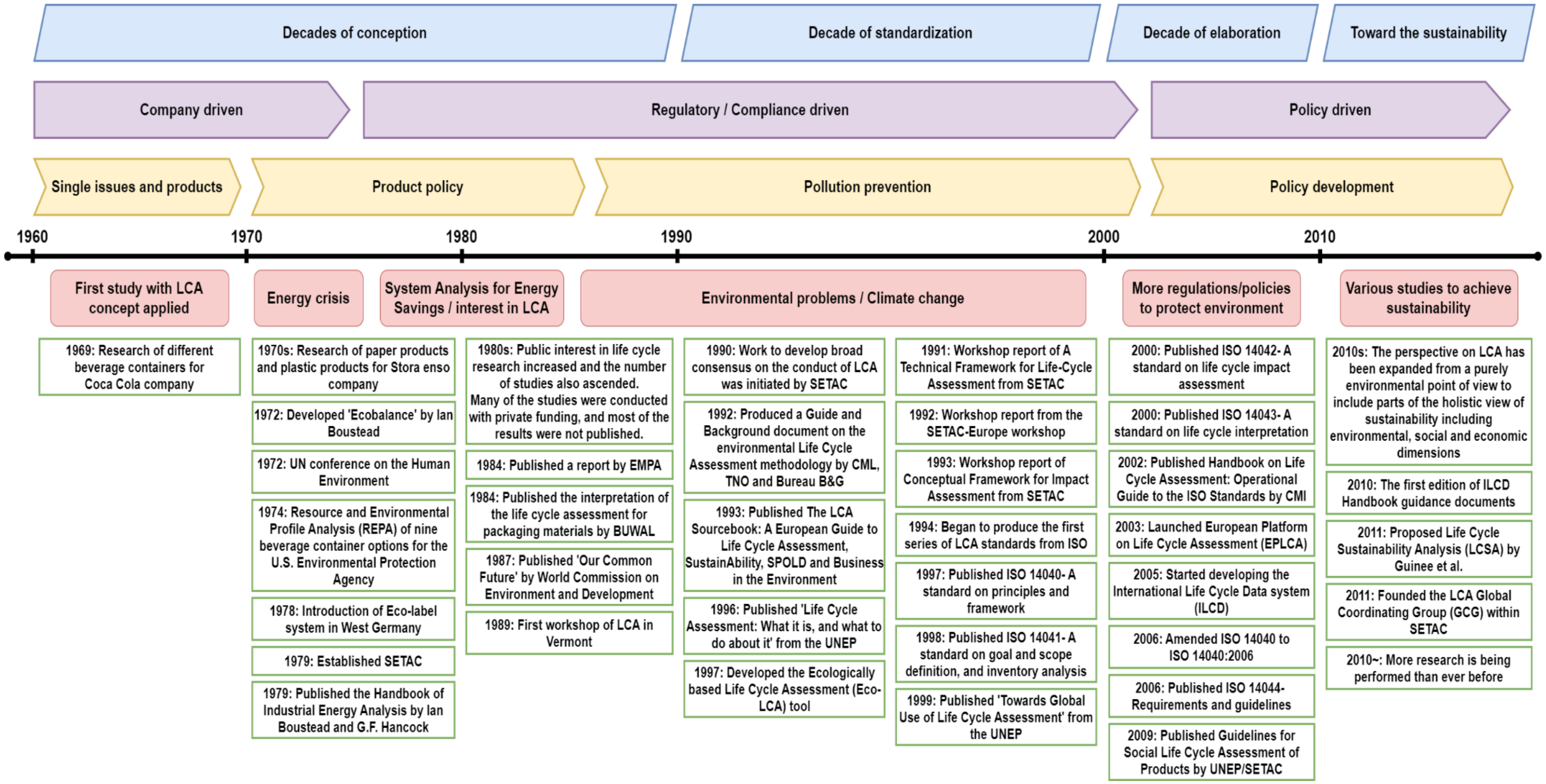


Figure 4-1. History of LCA

As the LCA history shown in Figure 4-1 (Singh and Bakshi, 2009, Hoffman and Schmidt, 1997, Guinée, 2002, Guinee et al., 2011, Brusseau, 2019, Frischknecht and Knöpfel, 2013, McManus and Taylor, 2015, Selmes, 2005, Damiani et al., 2021), the first LCA studies could be traced back to the late 1960s and early 1970s and were born limited to a schedule/regular process like manufacturing products in factories.

The study that introduced the concept of life cycle environmental impact assessment for the first time is recognised as an evaluation which examined the complete process of beverage container production to disposal. It was commissioned by Coca-Cola in 1969. As disposable products began to be commonly used, consumers appreciated the convenience they provided, but they also became worried about the environmental problems resulting from the use of disposable items. Nevertheless, from the perspective of a profit-driven company, beverage packaging was changed from bottles to disposable products, thereby eliminating the need to transport returnable bottles back to the factory and reducing the production costs of beverage containers. However, reasons were needed to address consumer opposition to environmental issues, and for this purpose, Coca-Cola requested the Midwest Research Institute to investigate the impact of product packaging on endowed resources and the environment. The institute compared various types of single-use containers with glass bottles, considering several factors such as energy consumption, waste generation, air emissions, and water pollution (Hunt et al., 1996). Following these pioneering studies, life cycle environmental assessments were performed on single items such as paper and plastic production during the 1970s. Until this point, most of the research had concentrated on simply determining which product had more benefits. Furthermore, it can be claimed that the company-driven environmental impact assessment was carried out because the majority of cases were commissioned by businesses for reasons such as profit and marketing.

(a) Decades of Conception (1970-1989)

It can be asserted that this period was the time when the concept of environmental impact assessment was conceived. In 1972, Ian Boustead conducted total energy calculation which was later known as the concept of 'Ecobalance' (Jensen et al., 1997, Boustead, 1992). Afterwards, Boustead continued related research, organised the methodology, and published that applicable to various materials as the 'Handbook of Industrial Energy Analysis' in 1979 (Boustead and Hancock, 1979). While in 1974, the U.S. Environmental Protection Agency introduced REPA for the first time (Hunt, 1974). Numerous unpublished studies were conducted utilising these terms. Nevertheless, due to the absence of a common framework and standard for environmental impact assessment, studies utilising the concept were conducted using different methods and procedures, which made it impossible to generalise the study results in terms of reliability.

In the 1970s, significant issues such as the oil shock (1973) and the energy crisis (1979) emerged. As a result of the shortage of energy and resources, interest in energy efficiency increased. Consequently, environmental assessment at the level of energy analysis was utilised as a broad range of tools used to identify potential impacts on various environmental indicators and resource depletion, and related studies were extensively conducted (Fink, 1997). Furthermore, environmental problems caused by pollution and waste began to receive public attention. Based on these interests and critical minds, in 1978, the Eco-label system was first introduced in Germany (Rubik, 1995), and SETAC, which contributed significantly to environmental assessment, was established in 1979 (Mogensen, 2000). However, this interest in the environment was short-lived, and research slowed down as a result.

In the 1980s, interest in the environment resurged, and various studies were actively conducted (Kemp, 1990). Hunt and Franklin expressed their interest in such a large environment using the expression 'dramatic re-awakening of environmental consciousness' (Hunt et al., 1996). In particular, the first workshop on LCA was held in Vermont in 1989, and environmental assessment was gradually carried out.

Until the 1970s and early 1980s, companies took the initiative in evaluating environmental impacts, but in the 1980s, as environmental regulations were created, regulatory/compliance-driven environmental evaluations began to be conducted.

(b) Decade of Standardisation (1990-2000)

Interest in the environment has rapidly increased since the second half of the 1980s due to various environmental influences. Initially, it showed local and regional characteristics but expanded to global problems, such as ozone layer destruction and climate change in the 1990s (OECD, 2001). As a result, it can be said that the awareness of pollution prevention has grown significantly. Thanks to this interest, academic interest in environmental impact assessment has also increased remarkably.

During this period, the concept of environmental impact assessment was established, and more detailed research was conducted. Additionally, the term Life Cycle Assessment (LCA) has come to represent environmental impact assessment, and standardisation has progressed. Through this, a framework for LCA implementation was established, and guidance was provided.

In the early 1990s, the Society of Environmental Toxicology and Chemistry (SETAC) developed standards (SETAC, 1993). SETAC continued discussions on the LCA methodology and framework so that the concept could be settled. In 1992, two LCA workshops were held. In the first workshop, an LCA component called 'Goal Definition and Scoping' was added, along with an agreement on the LCA framework. Based on this, a report on the LCA conceptual framework was published in 1993 by Fava (1993) and the following LCA framework was introduced as shown in Figure 4-2.

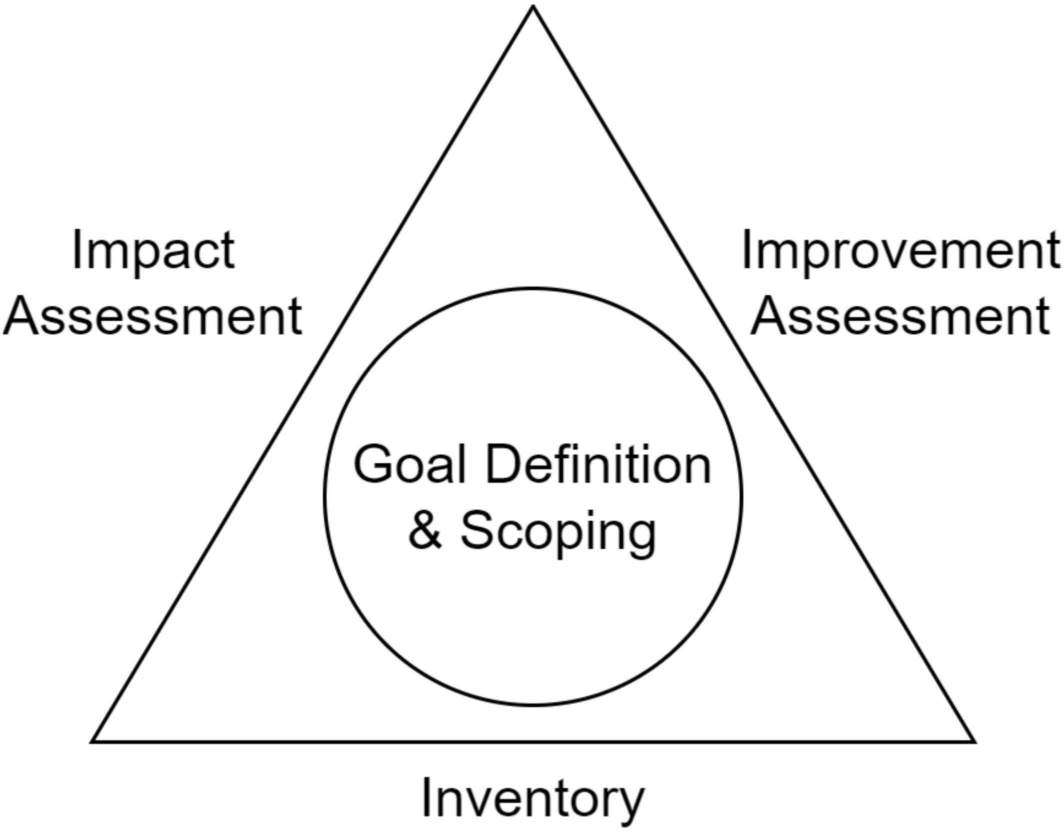


Figure 4-2. LCA framework introduced by SETAC

In the second workshop, discussions on data quality in LCA were conducted, and based on this, a report on LCA data quality was published in 1994 by Fava (1994). The United Nations Environment Programme (UNEP) published a report on the concept and execution method of LCA in 1996 and a report on the generalisation of LCA in 1999 (UNEP, 1996, UNEP, 1999).

The International Organization for Standardisation (ISO) specified the LCA method and carried out standardisation work. Accordingly, the SETAC standard was adopted and revised as an ISO standard in the late 1990s, through which ISO stipulated the large framework of LCA implementation and provided guidance.

- ISO 14040 Environmental management - Life cycle assessment - Principles and framework (1997) (International Standard Organization, 1997)

- ISO 14041 Environmental management - Life cycle assessment - Goal and scope definition and inventory analysis (1998) (International Standard Organization, 1998)

- ISO 14042 Environmental management - Life cycle assessment - Life cycle impact assessment (2000) (International Standard Organization, 2000a)

- ISO 14043 Environmental management - Life cycle assessment - Life cycle interpretation (2000) (International Standard Organization, 2000b)

Although these LCA frameworks were established, standardisation was not carried out for each detail, enabling flexible LCA performance rather than standardised evaluation.

Regulation/Compliance-driven environmental assessment, a trend from the 1980s, was continuously maintained in the 1990s, and environmental impact assessment was used as a tool to prepare measures to satisfy various regulations in response to global environmental problems.

(c) Decade of Elaboration (2000-2009)

Due to the emergence of continuous environmental problems and climate change, there was a significant increase in interest in the environment. Consequently, LCA research also increased considerably (McManus and Taylor, 2015). However, due to the lack of detailed standardisation of LCA methods by ISO and the absence of a common consensus on how to interpret some ISO requirements, various studies conducted at this time resulted in different approaches regarding system boundaries and allocation methods. As a result, elaborate discussions were carried out to identify factors that could hinder the consistency of LCA research in various aspects, such as system boundaries and calculation procedures.

In 2002, UNEP and SETAC launched an international life cycle partnership known as the Life Cycle Initiative. The primary objective of this initiative was to put lifecycle thinking into action and enable better data and metrics to determine consistent categories and generalisability of findings (Rosenbaum et al., 2008). Subsequently, in 2003, the European Platform on Life Cycle Assessment (EPLCA) was launched. UNEP and SETAC continued their partnership and published Guidelines for Social Life Cycle Assessment of Products in 2009 (Andrews et al., 2009).

In 2006, the ISO guidelines were revised and newly adopted. ISO 14040 was revised to ISO 14040:2006, and ISO 14044 were specified.

- ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework (2006) (International Standard Organization, 2006a)

- ISO 14044 Environmental management - Life cycle assessment - Requirements and guidelines (2006) (International Standard Organization, 2006b)

While ISO 14040 focuses on describing the concept and framework of LCA, ISO 14044 serves to specify the requirements for LCA and provide procedures and guidelines for implementation with framework as shown in Figure 4-3.

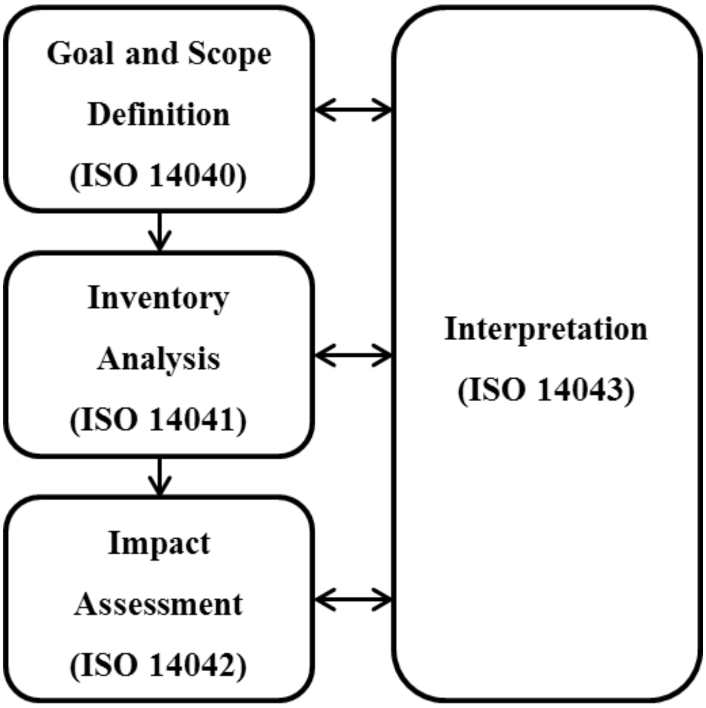


Figure 4-3. LCA framework (ISO 14044:2006)

During this period, more regulations and policies for environmental protection were introduced, and governments and organisations initiated policy-driven environmental movements.

(d) Toward Sustainability (2010 ~)

For the sake of protecting the environment and creating a better future, researchers have begun to conduct studies on achieving sustainability, which is a higher concept. Currently, LCA is being performed to evaluate the impact on the environment. However, when discussing sustainability, it must be considered not only the environment but also the economy and society. In other words, determining the sustainability of a product/system involves examining whether it can be economically utilised and socially acceptable from various angles, in addition to its impact on the environment. Consequently, it can be argued that this movement towards sustainability represents a way of thinking that prioritises the preservation of the environment. This is because sustainable products/activities are inherently linked to environmental preservation.

Several sustainability studies have been conducted as a name of Life Cycle Sustainability Assessment (LCSA), including the Life Cycle Sustainability Analysis in 2011 (Guinée and Heijungs, 2011). This trend represents a new direction for policy-driven environmental movements.

4.2. ISO standards

As explained in section 4.1, the currently used ISO standards is based on the revised version in 2006. Following this standard (ISO 14044:2006), the LCA general framework is guided as shown in Figure 4-3.

4.2.1. Goal and Scope

Defining the Goal and Scope is a crucial step in conducting a comprehensive and relevant LCA.

The goal defines the primary objective of the LCA study, which informs the methodology and study design. It should clearly state the reason for conducting the assessment, such as comparing environmental performance, identifying more emission points, or assessing the overall impact of a process. Additionally, the target audience and range of provisions or constraints should be identified in the goal step.

While the scope of the LCA outlines the system boundaries of the analysis, including the product or process being evaluated, the functional unit used for comparison, and the life cycle range to be included. The scope also specifies the environmental impacts and range of resources/data to be considered.

4.2.2. Life Cycle Inventory Analysis (LCI)

Life Cycle Inventory Analysis (LCI) is the second step and key component of LCA. The goal of LCI is to identify the environmental loads associated with a product or system and to provide a database of emissions from sources that exist in various routes (production plants, transportation vehicles for distribution, mining or farming methods, etc.).

In this stage, the data of inputs, outputs, and environmental loads of a product or system over its entire life cycle are collected and quantified. Then, it provides a comprehensive inventory of the resources consumed and the emissions released at each stage of the product's life.

In order to perform accurate LCA, collecting appropriate/reliable data at the LCI stage is the most important. Data is collected on the inputs and outputs of each stage of the product's life cycle, including the raw materials used, energy consumed, water/resources consumed, waste generated, and emissions released. The data is then compiled into an extensive inventory with a connection from upstream to downstream, including raw material extraction, manufacturing, transportation, use, and disposal.

4.2.3. Life Cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment (LCIA) corresponds to the third step of the four components of LCA, a systematic procedure for diagnosing potential environmental impacts of a product or system. It builds on the data collected in the LCI phase and provides predicted results by evaluating possible environmental impacts based on the calculated environmental loads.

The environmental load data that has been gathered is classified according to impact categories, namely global warming potential, eutrophication potential, acidification potential and etc, which were established during the Goal and Scope stage.

Following the definition of impact categories, the subsequent step in LCIA involves conducting Characterisation, which involves the quantification of the potential impact of an input or output unit on each impact category, using characterisation factors.

4.2.4. Interpretation

Interpretation constitutes the final stage of LCA, and is a critical step that involves the evaluation and diagnosis of LCI and LCIA results. It is closely linked to all the preceding stages and encompasses the provision of insightful and meaningful information about the environmental performance of a product or system.

A significant aspect of Interpretation is the identification of major environmental issues. By comparing and analysing data collected during the LCI stage, it is possible to assess the potential for reducing environmental loads through alterations in product design, manufacturing processes, or end-of-life management. Moreover, it can aid in determining the most significant impact categories by comparing the results of LCIA for each category.

Another essential point of this stage involves the evaluation of whether the outlined purpose and research boundary in the Goal and Scope stage are adequately reflected in the study. To achieve this objective, the Completeness analysis, Sensitivity analysis, and Consistency analysis methods are employed. Conducting these processes is essential to ensure the accuracy and reliability of the LCA results.

Lastly, this step culminates in drawing conclusions, specifying limitations, and providing recommendations based on the LCA results. Consequently, the information gleaned from this stage can guide decision-making towards more sustainable practices and communicate environmental sustainability concerns to stakeholders and decision-makers.

4.3. Limitations of current Life Cycle Assessment

While the current IMO’s environmental regulations and the GHG strategy envisage a reduction in operational carbon emissions, most recent research points out their shortcomings: although carbon-neutral fuels like grey hydrogen and ammonia produce no GHG emission in Tank to Wake (TtW) stage, they would produce greater amounts of emissions in Well to Tank (WtT) stage. Those fuels could possibly result in more emissions than those fossil fuels from a lifecycle perspective (Gilbert et al., 2018). To address this fact and the issues highlighted in Section 3.4 and bridge the research gap in environmental studies, Life Cycle Assessment (LCA) has been implemented in the shipping sector.

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 (Klöpffer, 2014).

However, as verified in section 4.1 on the history of LCA, LCA originated from an environmental impact assessment conducted for the production of a single product as shown in Figure 4-4. Hence, it is therefore fundamental that it was designed to evaluate the environmental impacts of static processes. However, unlike a factory that produces the same product under identical conditions, the operating environment and conditions of ships change with every moment and situation. Therefore, the existing LCA methodology has limitations in assessing the environmental impact of the shipping sector. Nevertheless, the International Maritime Organization (IMO) and its member state presently regard conventional LCA, which cannot cover dynamic process, as the most dependable tool for determining the holistic environmental impacts of marine vessels, without any doubt.

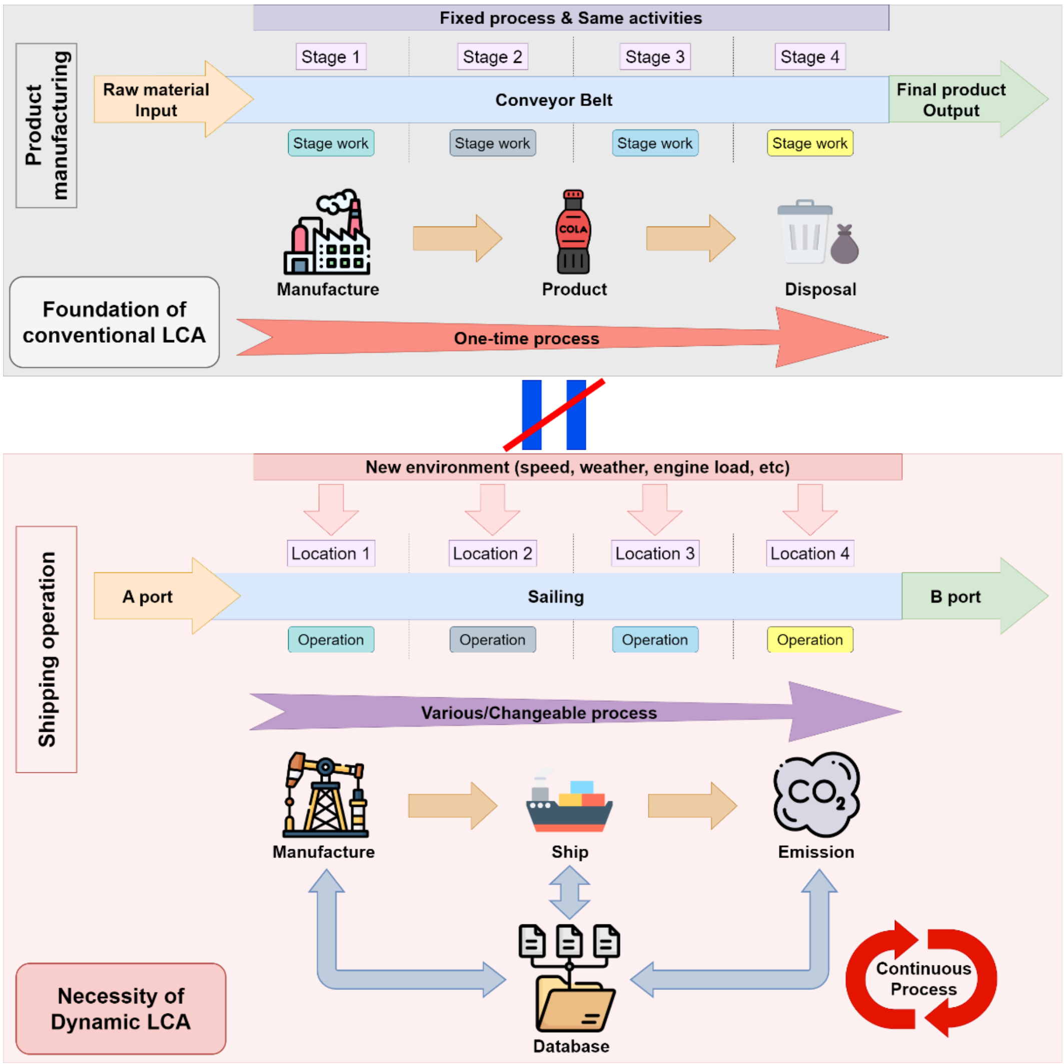


Figure 4-4. Necessity of Dynamic LCA

In this chapter, it is aimed to review the cases of LCA applied to the shipping industry, identify their limitations, and confirm the necessity of introducing dynamic LCA, as illustrated in Figure 4-4.

4.3.1. LCA in the marine industry

Recognition of LCA research and application to the marine industry have grown over the last two decades to understand the environmental impact of the shipping sector as a whole from the perspective of the life cycle. Through this trend, voluminous LCA research has been conducted. In these studies, considering the upstream stage of energy, they evaluated how substitutions such as introducing a new system to a ship are actually environmentally beneficial.

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 (Ellingsen et al., 2002), the National Maritime Research Institute of Japan developed LCA software for reliable LCI (Life Cycle Inventory analysis) data of cargo ships in 2005 (Kameyama et al., 2005), and Kameyama et al. (2007) developed 'LIME' which is a comprehensive life cycle impact assessment (LCIA) methodology. 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 (Popa et al., 2014, Chatzinikolaou and Ventikos, 2014). In 2018, Wang et al. (2018) emphasises 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. Some examples of marine fuels are as follows: LCA study on main fossil fuels used in ships (Bilgili, 2021) and on LNG as ship fuel (Hwang et al., 2019); LCA in marine fuels produced in Saudi Arabia and compared it to LNG (El-Houjeiri et al., 2019); a study on the difference in environmental impact when using HFO and LNG as fuels (Sharafian et al., 2019); environmental assessment according to ship specification for ships using LNG (Jang et al., 2021); research on electric propulsion ship in the aspect of the lifecycle (Jeong et al., 2020, Jeong et al., 2022); and lifecycle research on various alternative fuels (Gilbert et al., 2018, Perčić et al., 2020, Bilgili, 2021, Xing et al., 2021).

As for power systems, some remarkable studies were conducted: applying a solar panel to a ferry (Wang et al., 2019), identifying a greener power system (Ling-Chin and Roskilly, 2016a) and LCA study on hydrogen fuel cell (Jang et al., 2022, Perčić et al., 2022).

In addition to this, there have been LCA studies conducted on the scrubber system, which is assessed as an alternative that can comply with sulphur oxide regulations while using existing marine fuels as it is. Ma et al. (2012) has evaluated its life cycle performance, while Jang et al. (2020) have compared the environmental impact of various types of scrubber systems in terms of their life cycle, using a new methodology called Prametric-Trend Life Cycle Assessment (PT-LCA).

Overall, the series of past LCA research applied to the marine sector above is strong evidence of the effectiveness towards net-zero and cleaner shipping. Based on this effort, LCA has been now highly acknowledged across industries. The European Commission adopted a proposal of ‘Fit for 55’ to reduce GHG emissions by at least 55% by 2030 and make the EU climate neutral by 2050 across all EU industrial sectors (European Commission, 2021). The FuelEU Maritime initiative was published in July 2021 as maritime strategies for ‘Fit for 55’. More importantly, this initiative urges the EU shipping sector to measure and control GHG emissions through LCA. As a standardisation process, the FuelEU Maritime initiative has first introduced LCA guidelines for maritime fuels, which are proposed to be applied in 2025. Similarly, IMO has also been grappling with developing new guidelines equivalent to EU LCA guidelines since 2018 and its first draft version will be finalised in late 2023.

Nevertheless, these studies also clearly expose the inherent limitations of the conventional LCA approach which are fundamental problems that serve the purpose of this thesis and require further improvement to ensure that this method of environmental assessment is properly adopted and used in the shipping sector.

4.3.2. Shortcomings of current LCA approach

Since 2000, as mentioned earlier, researchers in the maritime sector started to borrow LCA methods from other industrial applications and tried to estimate lifecycle emissions for ships. However, their attempts were fundamentally exposed to pitfalls in that early LCA has been to evaluate static processes, case-specific scenarios or estimated/assumed sources due to lack/absence of data. These characteristics of conventional LCA have made it difficult to properly implement the dynamic behaviour of ships, general observation and appropriate/reliable environmental assessment.

The first limitation identified pertains to the applicability of study results to other cases, as the studies conducted were limited to specific cases. 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. (2019) 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. That means, 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; Research of Atodiresei et al. (2017), Jeong et al. (2020), El-Houjeiri et al. (2019) and Hwang et al. (2019) targeted a specific region. In addition, Kameyama et al. (2007), Chatzinikolaou and Ventikos (2014) and Ling-Chin and Roskilly (2016a) chose specific ship type. The case-specific nature of the studies represents a significant limitation, in that the study outcomes are only valid under the conditions of the study and cannot be extrapolated to other situations. 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.

Not only this, Strazza et al. (2010) did not clearly set the fuel production method, and Ling-Chin and Roskilly (2016b) performed LCA assuming the amount of energy produced by the solar PV system. Research by Ma et al. (2012), Nian and Yuan (2017), Jang et al. (2020) and Jang et al. (2021) calculated the fuel consumption assuming the engine power as the maximum continuous rating (MCR), and Gilbert et al. (2018) and Sharafian et al. (2019) had ambiguity in the environmental impact assessment because ship specifications were not considered. Through these cases, it can be seen that the environmental impact in the maritime sector has not been properly analysed to cover the entire life cycle from a holistic point of view. In other words, lots of parts are replaced by predictions or assumptions, which obscure an intuitive assessment of how much a ship's activities really affect the environment. As a result, it was not possible to suggest which fuel/energy source should be used in what way to become a true greener system in the shipping sector.

Lastly, conventional LCA practices are overly laden on static estimation as providing perpetual results indicative of lifetime emission levels. Hence, they lack the implementation of dynamic behaviours of ships subject to incessant changes. These limitations, which are inherent in conventional LCA practices, can be observed in the EU/IMO directives mentioned above.

As shown in Figure 4-1, the first LCA studies could be traced back to the late 1960s and early 1970s and were born limited to a schedule/regular process like manufacturing products in factories. Since 2000, as mentioned earlier, researchers in the maritime sector started to borrow LCA methods from other industrial applications and tried to estimate lifecycle emissions for ships. However, their attempts were fundamentally exposed to pitfalls in that early LCAs were created to evaluate static processes that were difficult to properly implement the dynamic behaviour of ships. The upper mentioned LCA studies in the marine sector have yielded outstanding research outcomes, enabling a comprehensive understanding of the environmental impact of the shipping sector, and facilitating the development of countermeasures to address it. Nonetheless, limitations inherent to the conventional LCA methodologies have been identified, including their inability to conduct general observation, offer continuous environmental impact results, and adequately reflect the dynamic and ever-changing characteristics of ships.

4.4. Research gap identification

Shipping is a global and highly dynamic activity. Ships are always subject to incessant changes in fuel properties, operating/weather conditions, voyage plans and energy management strategies, etc. Indeed, those parameters are key inputs for lifecycle environmental impacts for ships. As a result, ships are highly likely to produce varying levels of emissions during any given period of time.

However, it was identified that the conventional LCA method is not highly relevant for implementing dynamic analysis because it also relies on the existing database. Due to these characteristics, 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 new power sources such as the solar PV system and electric propulsion, which will make great differences in the environmental results of ship performance.

This existing data-based nature also forces researchers to substitute guesses or assumptions for these parts in the absence of existing data, which becomes a major obstacle providing research ambiguity. As a result, the existing method renders general observation unfeasible, and the results of research do not have universality and make narrow proposals possible due to ambiguity and uncertainty.

From the literature review, it is confirmed that research that is able to resolve the ambiguity caused by predictions and assumptions, and in which various aspects mentioned are adequately considered is essential. This research gap needs to be overcome through the enhanced LCA method and advanced research methodology proposed in this thesis. Only the evolved methodology based on the current LCA can only provide the right energy solution and the way toward net zero to the shipping field.

Another significant research gap identified regarding the introduction of LCA in the shipping sector pertains to the piecemeal and one-time provision of LCA results.

In a static environment where products are manufactured following a predefined process, it may not be necessary to update LCA results continuously. However, unlike such environments, ships operate in dynamic conditions in which their operational circumstances vary, leading to diversified environmental impacts. Consequently, it is not feasible to accurately ascertain the environmental impact of a ship based on fragmented LCA results.

In response, the IMO's environmental indicator, Carbon Intensity Indicator (CII), has been programmed to continuously update the ship's environmental performance by regularly iterating the calculations with updated parametric inputs. However, as expounded in section 3.3, the CII implemented by the IMO is subject to certain limitations. Specifically, it is limited to assessing CO_2 emissions and cannot provide a comprehensive evaluation of the overall environmental impact. Furthermore, although the environmental impact is updated periodically, the cycle is lengthy, spanning a year.

In this context, a novel LCA approach should be proposed to implement continual monitoring/estimation and update of environmental performance in response to any change in parametric inputs. It is believed that this thesis can suggest an effective solution to the proper arrival of LCA into the marine sector. Hence, it is to implement a dynamic feature into the conventional LCA process by proposing an enhanced LCA model.

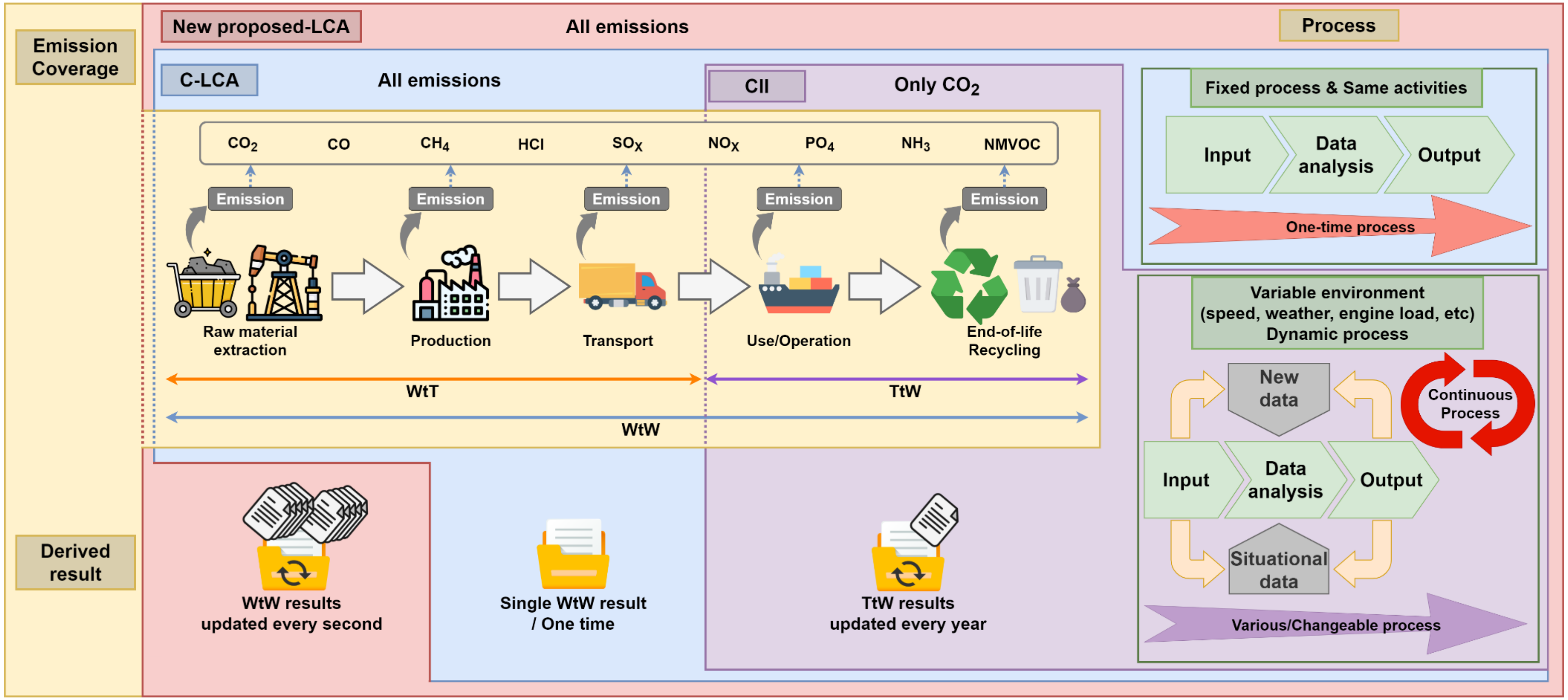


Figure 4-5. The superiority/necessity of new proposed-LCA compared to conventional LCA (C-LCA) and CII

Table 4-1. Comparison of characteristics between environmental impact assessment methodologies

Comparing methods of environmental impact				
	Scope	Interval	Pros	Cons
CII	TtW	Annual	• Updating data/results annually	• Considering only the use/operation aspect • Only focusing on CO_2
C-LCA	WtW	One time calculation	• Holistic evaluation/analysis	• Using past data • Past performance • No update on the results
New proposed-LCA	WtW	Every second (continuous update)	• Updating Data/Results in real time • Holistic evaluation/analysis • Using real-time/actual data	-

As can be seen in Figure 4-5 and Table 4-1, the new methodology, which will be suggested in this thesis, is targeted to combine the merits of CII, continuous and consistent inspection and update of results, with the benefits of LCA, which captures the environmental impact from a holistic perspective from upstream to downstream. In addition, it aims to be possible to supplement the shortages of CII, which covers only the fuel consumption aspect and focuses on only CO_2 without total environmental impact, and the disadvantages of the conventional LCA, which cannot derive results reflecting different situations when fuel/system is changed and does not provide continuous results.

5. METHODOLOGY

5.1. Introduction

In Chapter 3, a number of activities carried out in the shipping sector to reduce emissions were identified. Although these activities are commendable, it was concluded that they are insufficient for achieving truly green and net-zero shipping. This confirms the necessity of introducing LCA in the shipping field.

However, after reviewing the background, application, and methodology for which LCA was created in Chapter 4, it was found that there are pitfalls in that the environmental impact generated by ships cannot be properly grasped by conventional LCA.

In order to remedy identified shortcomings of current LCA, the enhanced and advanced LCA, called dynamic LCA, is suggested in this thesis as shown in Figure 5-1.

The Dynamic LCA methodology has the capability to consistently and iteratively capture the characteristics of ships operating in a dynamically evolving environment. This enables the mitigation of limitations inherent in conventional LCA, which typically provides one-time assessments, and facilitates the continuous provision of accurate and relevant environmental impact results. Furthermore, by employing modelling and simulation, the reliance on existing data can be minimised, leading to enhanced precision and reliability of the outcomes, as well as the establishment of an extensive database. With these capabilities, the Dynamic LCA methodology allows for thorough evaluations and enables the ongoing utilisation of results as feedback and new data, fostering the implementation of various follow-up measures and actions.

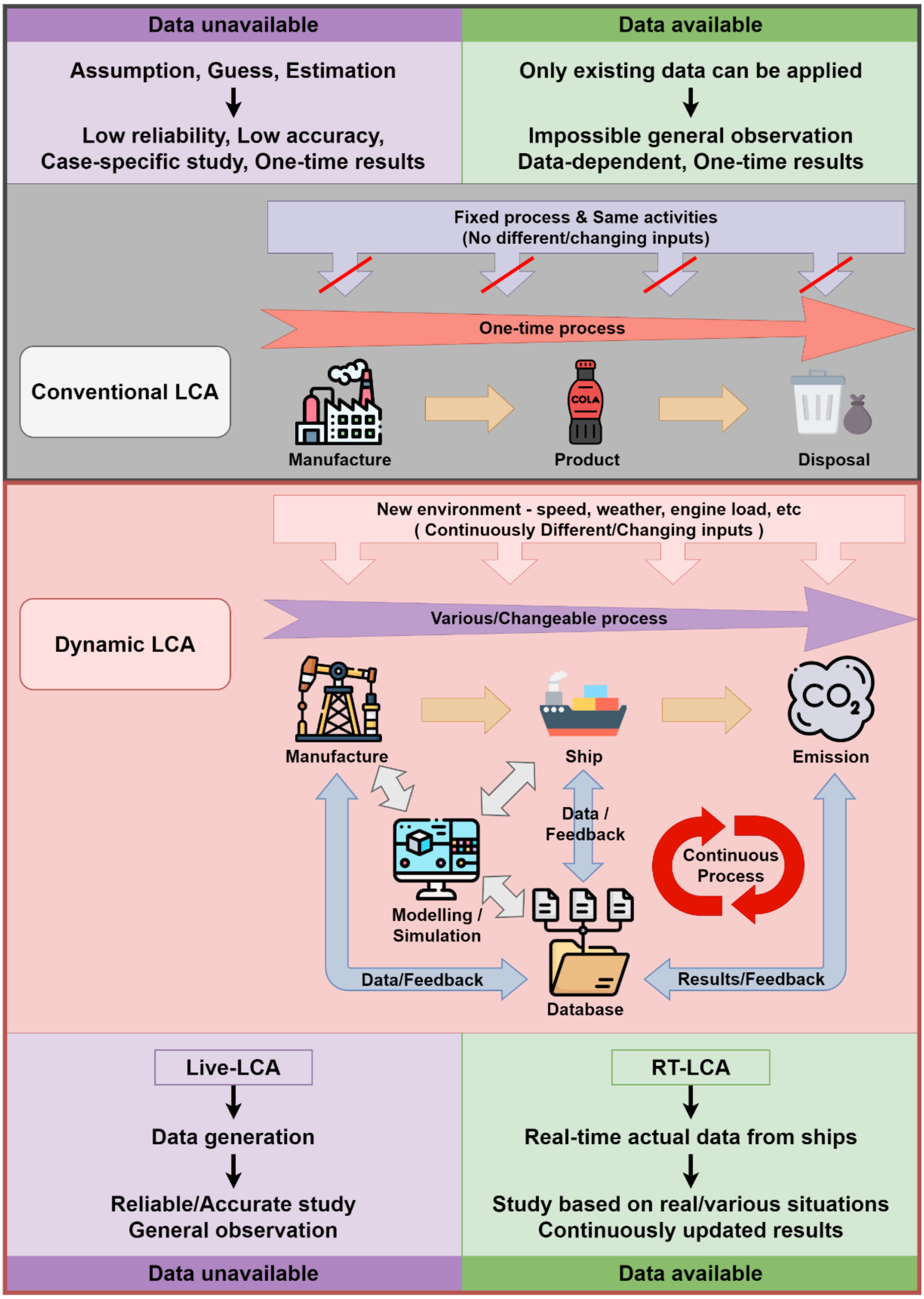


Figure 5-1. Introduction of Dynamic LCA

5.2. Dynamic LCA

The current methodology relies too much on obtained databases, which are set up based on past data and cannot consider current situations. Furthermore, the reliability of the study is reduced if data is missing, as it is often replaced with assumptions or guesswork. This situation occurs frequently for ships whose circumstances are constantly changing, leading to many parts being replaced with data through estimations or speculations. In addition, the environmental impact of solar PV systems, which exhibit significant variations in energy production depending on environmental circumstances, can result in a significant ecological impact difference. To address these issues and fill the gaps in existing LCA studies, a new LCA methodology is proposed that generates data, called Live-LCA, rather than blindly assuming or guessing the uninvestigated data.

Another research gap is that the existing LCA is a methodology developed for a static process, making it difficult to cover ship activities operating in a dynamic environment. Therefore, previous studies have omitted or assumed too many parts to cover the aspect of these dynamic circumstances, hindering adequate and reliable environmental assessment. To bridge this research gap, this thesis proposes a new methodology, Real-Time LCA (RT-LCA), that can properly reflect dynamic driving. This technique can significantly improve the disadvantages of static LCA by clearly identifying and providing the ship's environmental impact in real-time.

5.2.1. Live-Life Cycle Assessment (L-LCA)

The LLCA methodology was designed to address the limitations of relying solely on existing data by generating data through simulation and/or experimentation, and to respond to ambiguity. This means that the accuracy and reliability of research can be increased by generating data through simulation and/or experimentation in the absence of data on ever-changing ship operating conditions. Moreover, the LLCA methodology replaces many parts with assumptions and expectations, making the results case-specific, and allowing clear overcoming of the limitations of previous LCAs that hindered general observation.

The LLCA methodology can offer a way to investigate previously unexplored facts and confirm the overall effects of new technologies, without being overly laden with a fixed dataset. Furthermore, it can quantitatively suggest the relationships between variables, such as different assumptions, inputs, scenarios, types of technologies, ship specifications, business cases, local/global conditions, and so on. Figure 5-2 illustrates the key features of LLCA in comparison to the conventional LCA.

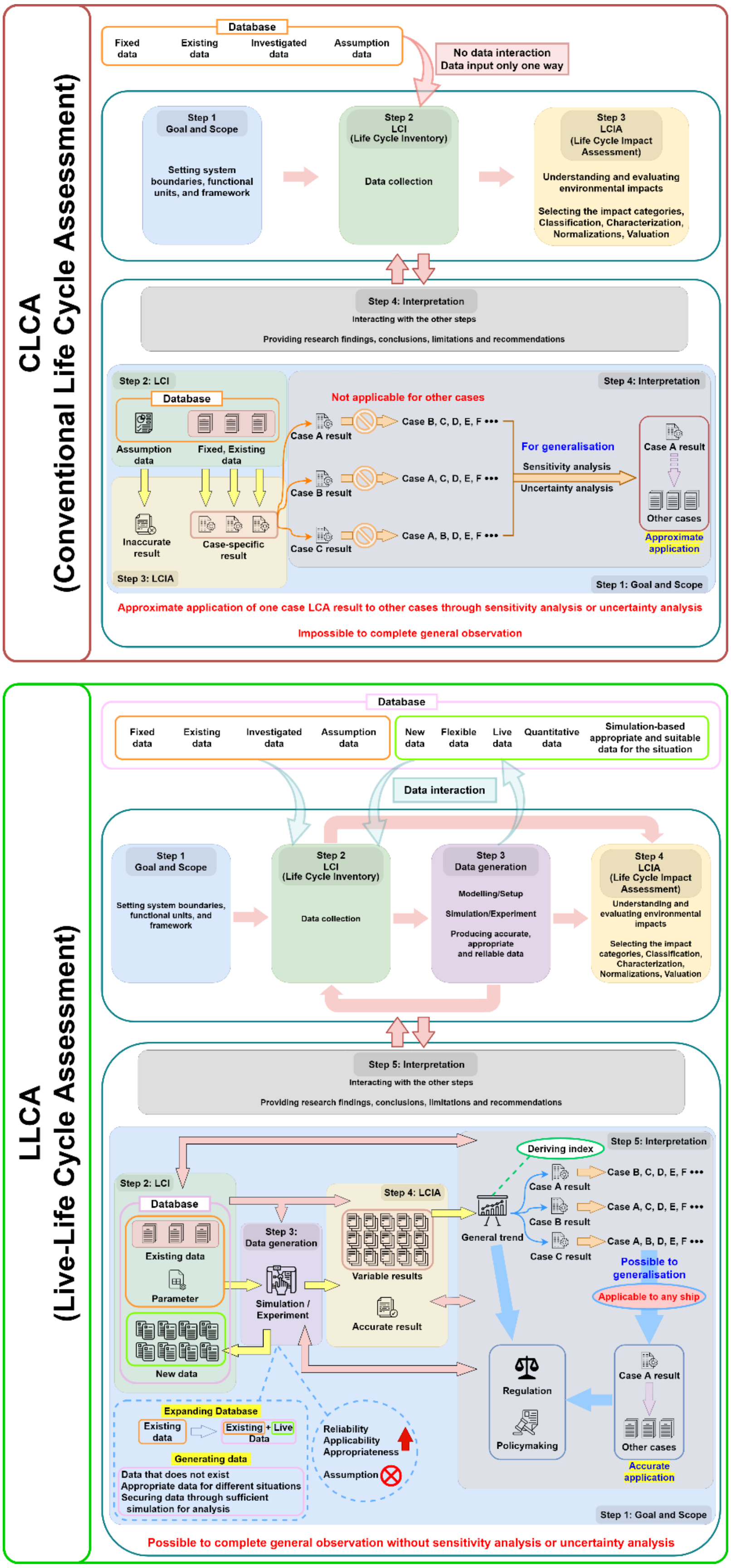


Figure 5-2. Live-Life Cycle Assessment framework and methodology compared to conventional LCA

As shown in Figure 5-2, 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.

5.2.2. *Real-Time Life Cycle Assessment (RT-LCA)*

RT-LCA is proposed to embody an immediate and lifelong process for real-time maritime environmental impacts. A key functionality of RT-LCA is to utilise live and continuous data in real time so that it keeps updating the performance of a subject ship from a lifecycle perspective.

Figure 5-3 compares the differences in process between the conventional LCA and RT-LCA. The RT-LCA generally follows the same steps as conventional LCA methods based on ISO guidelines; 1) goal and scope, 2) lifecycle inventory analysis (LCI), 3) lifecycle impact assessment (LCIA), and 4) interpretation. A key difference of RT-LCA lies in continuously iterative data entry, processing, and display of results every second, providing greater opportunities for monitoring, detective, proactive and corrective actions onboard if necessary.

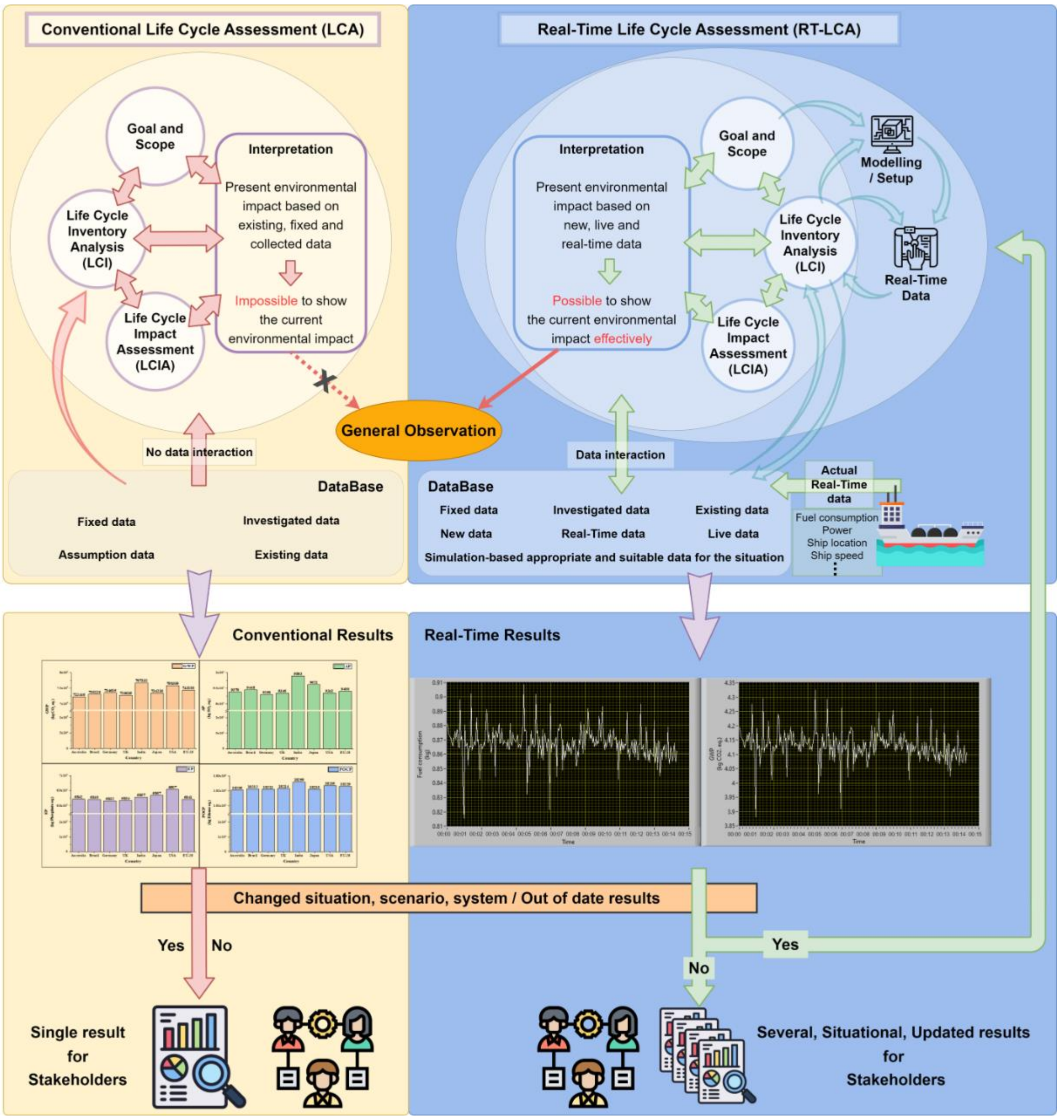


Figure 5-3. Comparison between conventional LCA and Real-Time LCA

As given in Figure 5-3, a fundamental shortcoming of conventional LCA is attributed to its limited data access and processing method. High reliance on outdated data and irreversible processing methods is not able to enable it responsible for the ship dynamism whose operating patterns, bunkering, and service routes are ceaselessly changing.

Conventional LCA may be useful to estimate emission levels in the past but hardly predict future emission levels later on. In other words, a serious drawback imposed on the conventional LCA is that there is no process for continuous updates of results in response to changes in various environmental factors in shipping. Hence, immediate feedback from any corrective action is not available with the conventional LCA.

RT-LCA proposed in this thesis is a method of collecting/processing actual data in real time (Domínguez-Patiño et al., 2014, Schachinger and Al-Lami, 2018). The continual data transmission from actual sensors and onboard monitoring systems is applied for the LCA and its iteration for continual updates in results. An iterative process is repeated every new second, thereby results are continually updated with the display of historical performance tracking over time. As a result, emissions and environmental impacts can be identified/interpreted in real time. This format of RT-LCA results is greatly helpful for ship operators to conduct rapid judgment and corrective action if needed. Indeed, it is an enhanced LCA approach that dresses a feature of CII on a conventional LCA process.

5.3. Chapter summary and conclusions

Advanced methodology, named Dynamic LCA, for utilising in this thesis was proposed and presented in this chapter.

Specifically, the first one of Dynamic LCA methodology is Live-LCA (L-LCA), which can overcome the limitations of conventional LCA methodology that heavily rely on secured databases and resort to assumptions or predictions when data is unavailable. The second one is Real-Time LCA (RT-LCA), which is applicable to the dynamic activities in the shipping field unlike previous model suitable only for static processes. This novel LCA method allows for general observations that were not feasible with existing methodology and facilitate the derivation of more accurate and reliable results.

The primary distinction between the two is the availability of data. L-LCA was designed to generate and use data through an appropriate method when the required data cannot be obtained. Conversely, if the essential data can be obtained in real-time, RT-LCA is intended to conduct an accurate environmental impact assessment immediately using it.

Case studies that apply these methodologies are conducted in the following chapters to demonstrate their superiority over conventional LCA methodology.

6. ELECTRIC PROPULSION SHIP USING SOLAR PV WITH L-LCA

6.1. Introduction

As reviewed in Chapter 4, existing LCAs heavily rely on past research data. For this reason, it is not possible to accurately evaluate the environmental impact of ships using renewable energy, which has been the subject of recent discussion, using the methods that assess the environmental impact of stationary situations based on previously studied data. This is because there is no previous data available in the case of producing varying amounts of energy based on continuously changing environmental factors. Consequently, these parts have to be substituted with assumptions or predictions, which leads to inaccurate and unreliable LCA studies. Therefore, since conventional LCA methods are incapable of examining how the same PV electric vessel could have significant differences in technical and environmental performance based on power production methods, service area, and regional climatic conditions, a case study was conducted to bridge this research gap.

This case study was conducted to demonstrate the effectiveness of the Live-LCA methodology, which generates data in a suitable manner in the absence of relevant data, by presenting how it overcomes the aforementioned limitations. The study presented a case for achieving more reliable and accurate LCA performance through data generation. Furthermore, the importance of the Live-LCA methodology was emphasised by denoting the potential for different results when studying the same case using conventional LCA methods.

6.2. Case study

Figure 6-1 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.

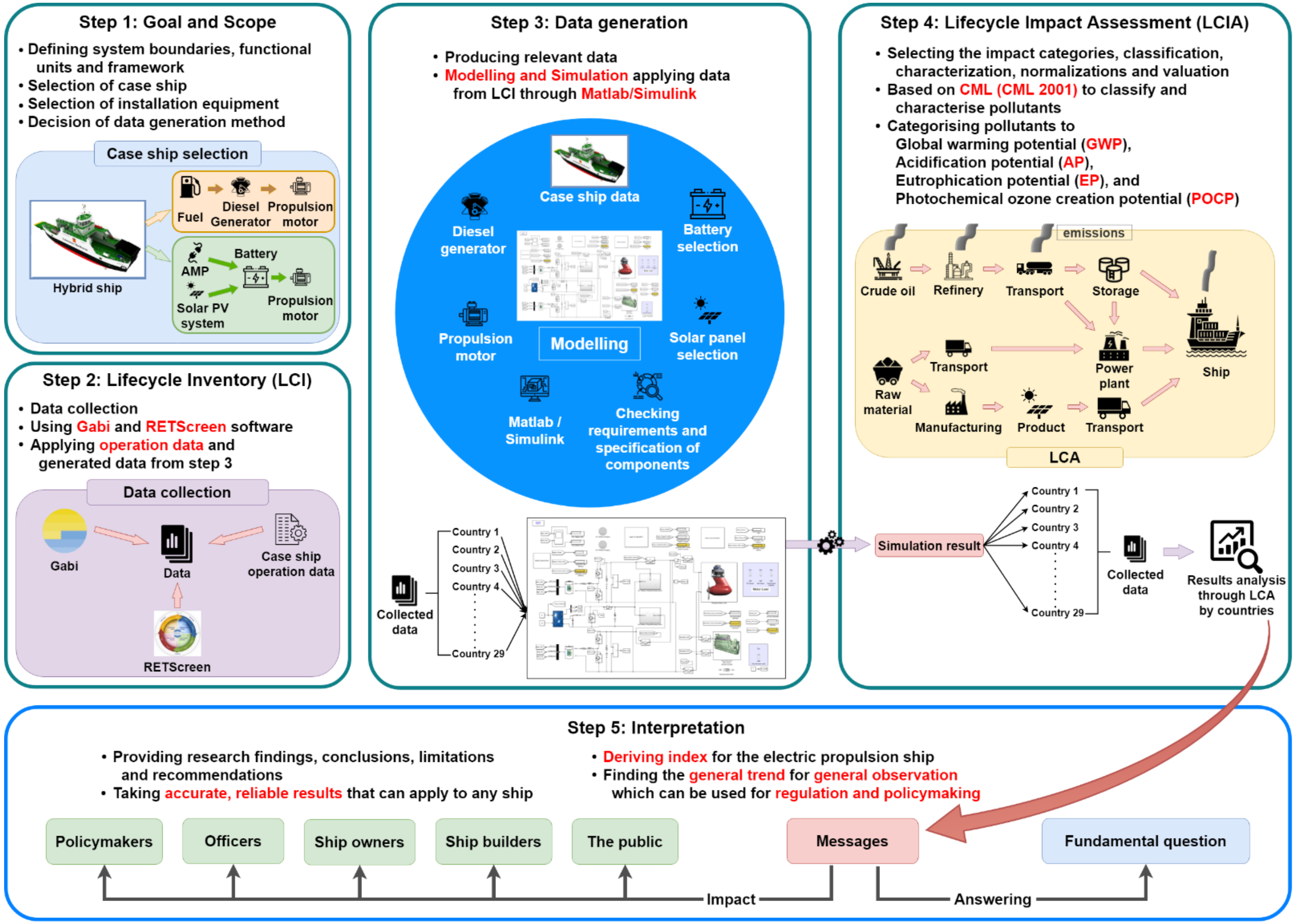


Figure 6-1. Schematic representation of a case study

6.2.1. 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 case study was proposed to find the answer to the fundamental question arisen in Section 6.1 to estimate the holistic environmental benefits/harms of PV electric ships under various operating scenarios illustrating the goal and scope of the case study.

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 were modelled with MATLAB/Simulink software based on a simulation time of 100 hours in MATLAB R2022a version to estimate the power production/consumption during the voyage.

(a) Electric propulsion ship

Based on the current practice of the case ship engaged in the West-Scotland coastal service (Karimi et al., 2020b), three credible operational scenarios will be investigated as below:

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

   To ascertain and compare the environmental impact of electricity production using diesel fuel onboard, diesel produced in Australia, Brazil, Germany, the UK, India, Japan, the USA, and the average data of EU-28 was selected. It was assumed that these diesel fuels would be loaded and utilised on the case vessel.
2) Full battery mode (Case 2): the electric energy used by propulsion motors is supplied from the inland electricity grid.

   To assess and compare the environmental impact of electrical energy, it was assumed that electrical energy produced in 29 countries (Australia, Belgium, Bulgaria, Brazil, Cyprus, Germany, Denmark, Estonia, Spain, Finland, France, the UK, Greece, Ireland, India, Italy, Japan, Lithuania, Latvia, Malta, the Netherlands, Norway, New Zealand, Poland, Portugal, Romania, Sweden, Slovenia, and the USA) was supplied and utilised by the case ship.

   For this case, it is necessary to install an adequate capacity of battery. In this case study, the required battery capacity for navigation was calculated and provided; however, the impact of the increased weight and installation area compared to the battery installed in the actual case ship was not considered within the scope of this case study.
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.

   To determine the energy production capacity and environmental impact of the solar PV system installed on the case ship when operated in a specific country, the amount of energy generated by the solar panels was calculated/simulated based on the environmental conditions of that country. This process ensures accurate estimation of solar panel energy production for reliable results.

In this case study, it was assumed that the solar panel installation area constitutes 80% of the total ship area. Furthermore, the impact of increased weight and required installation space resulting from the addition of solar panels, which were not present in the existing case ship, was excluded from the scope of this study.

(b) <u>Case ship selection</u>

A hybrid RoPax ferry built by the Scottish shipyard of Ferguson Marine was selected as the case ship as shown in Table 6-1. 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 6-1. Information of the case ship

<table>
<tr><th colspan="5">Case ship size and specification</th></tr>
<tr><td>Length</td><td colspan="4">39.99 m</td></tr>
<tr><td>Beam</td><td colspan="4">12.2 m</td></tr>
<tr><td>Draught</td><td colspan="4">1.73 m</td></tr>
<tr><td>Deadweight</td><td colspan="4">100 t</td></tr>
<tr><th colspan="5">Operation data of the case ship in a day</th></tr>
<tr><td></td><td>Hours</td><td>Shaft power (kW)</td><td>Total load (kW) (including hotel load and losses)</td><td>Daily total power consumption (kWh/day)</td></tr>
<tr><td>Transit mode (9 knots)</td><td>6.0</td><td>267.5</td><td>354</td><td>2124</td></tr>
<tr><td>Manoeuvring mode</td><td>0.6</td><td>120</td><td>152</td><td>91</td></tr>
<tr><td>Port mode</td><td>3.73</td><td>72</td><td>104</td><td>388</td></tr>
<tr><td>Total operation</td><td>10.33</td><td>-</td><td>-</td><td>2603</td></tr>
<tr><td>Overnight</td><td>13.67</td><td>-</td><td>-</td><td>-</td></tr>
</table>

6.2.2. 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 analysed 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:

(a) 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 (Sphera Solutions, 2023) as shown in Figure 6-2. LCA is followed by simulations of the case ship sailing on power supplied by each country.

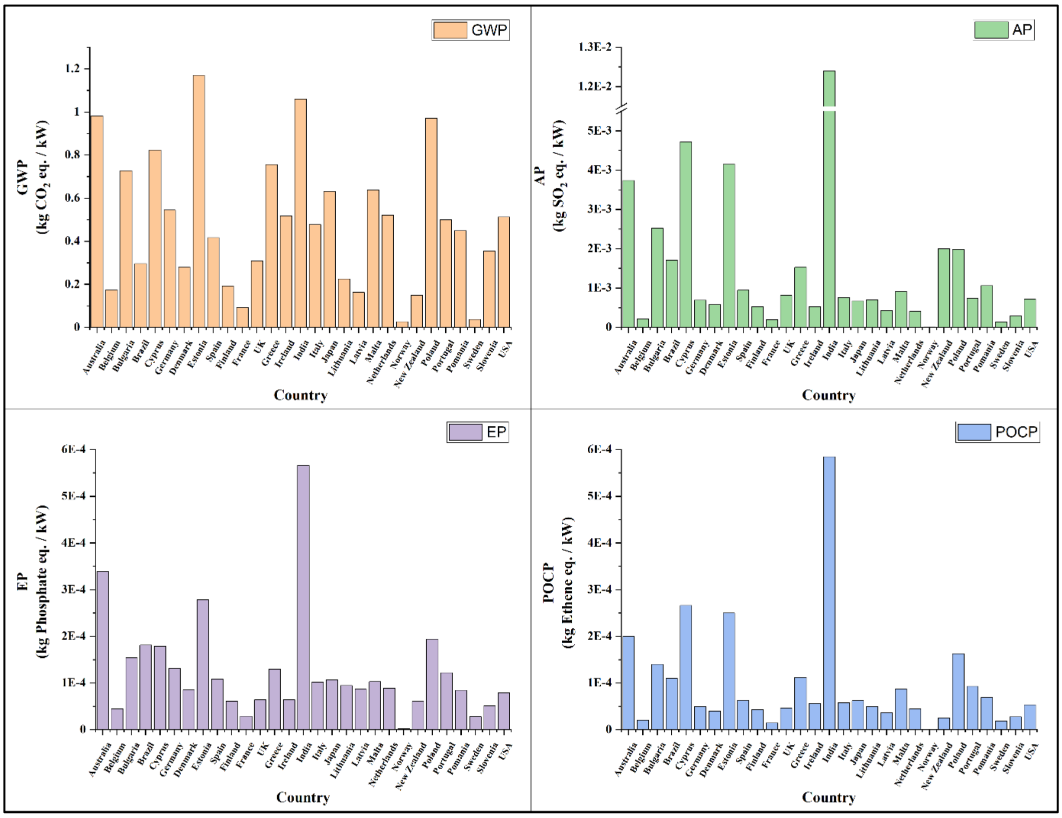


Figure 6-2. Environmental impact per 1kW of producing electricity in each country

(b) RETScreen

For simulation of the Solar PV system onboard, weather data for the 29 countries were collected through RETScreen software (Government of Canada, 2023) as shown in Figure 6-3. By inputting the monthly average of solar irradiance (W/m^2) 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 6-4. This simulation was conducted based on 100 hours and shows the clear different amounts of energy produced by solar panels by irradiance (W/m^2) and temperature (℃).

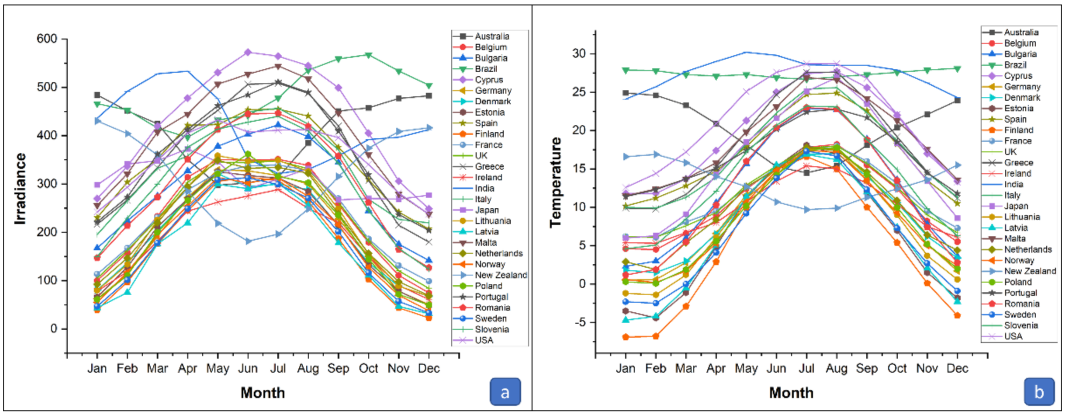
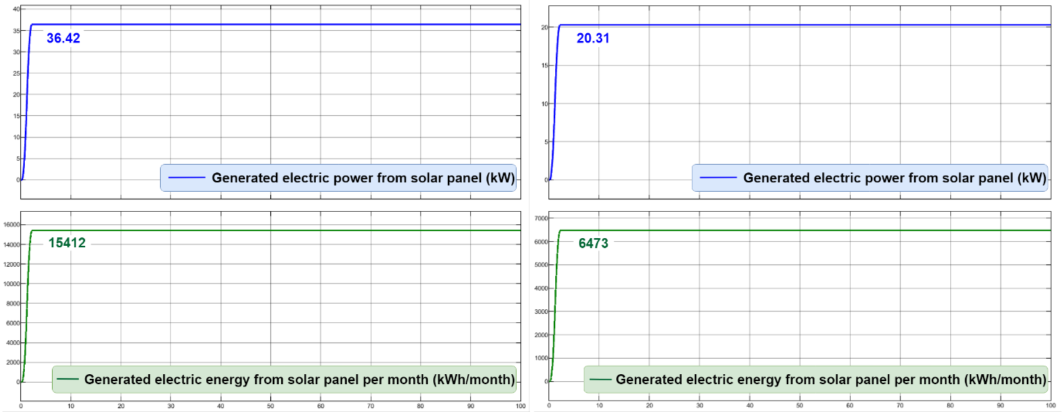


Figure 6-3. Graphs monthly irradiance and temperature for the 29 countries



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

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

Figure 6-4. Different electric production levels of kW and kWh from installed solar panels across environmental factors, (a) in the US in May, (b) in the US in December

6.2.3. Step 3: Data generation

As the key feature of the Live-Life Cycle Assessment, this Step 3 was designed to produce relevant data, such as electric energy produced by solar panels and storing/discharging it to/from the battery 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.

(a) Electricity distribution system

As considered in section 3.2.1, reflecting several benefits and current industry trends, the case ship was modelled on the basis of a DC system.

(b) 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 (Wen et al., 2016, Geertsma et al., 2017a). Figure 6-5 briefly shows the difference in system configuration as well as lifecycle energy supply stages between the two systems.

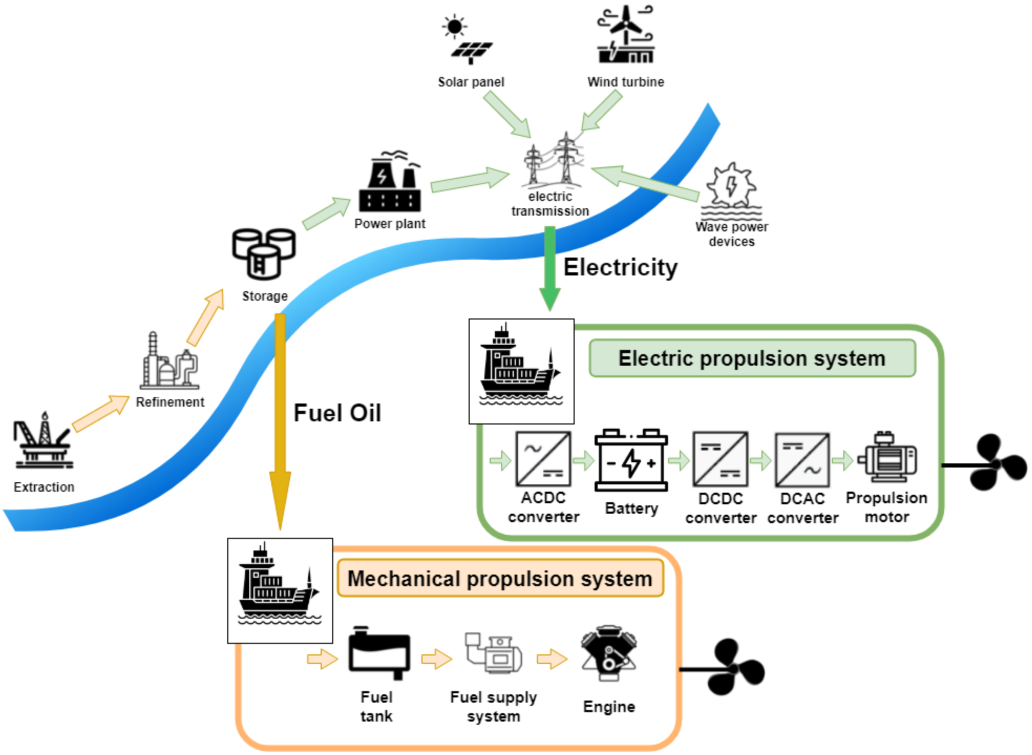


Figure 6-5. Propulsion systems

(c) Modelling

Based on the concept of electric propulsion ship as shown in Figure 6-6, the modelling is completed by using MATLAB/Simulink by comprehensively considering the following parts of Table 6-2.

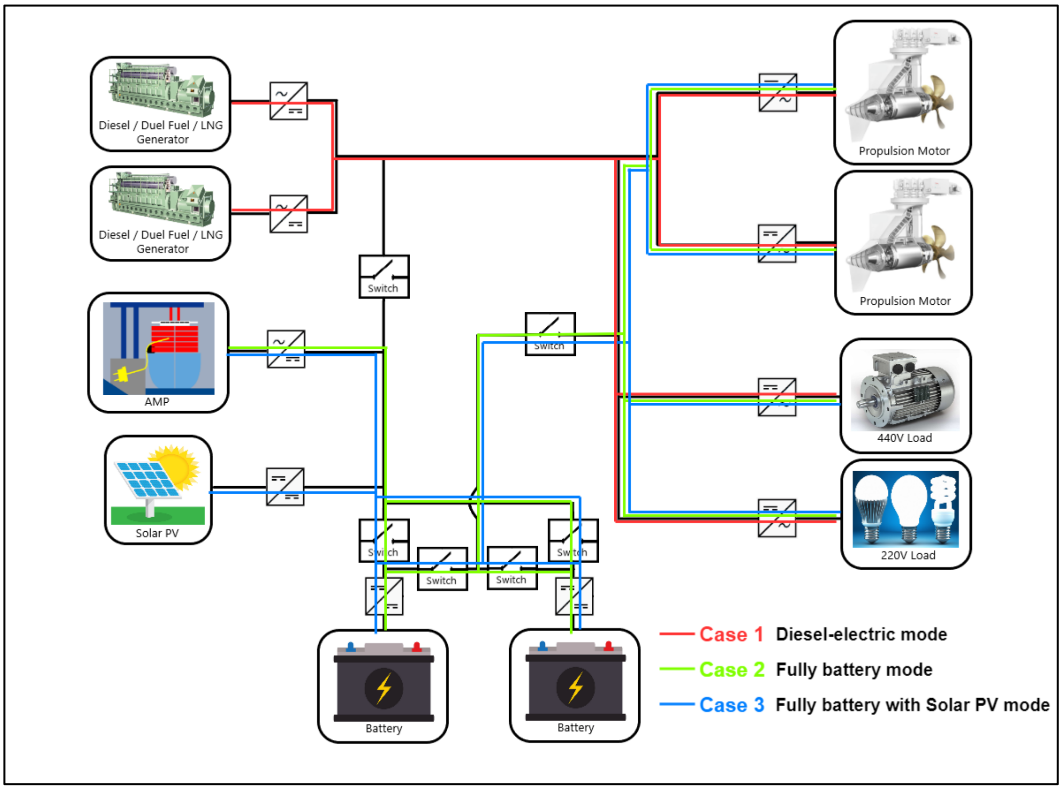


Figure 6-6. Conceptual design of the case ship

Table 6-2. 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 case study, 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 6-7 which clearly indicates that batteries are an excellent energy storage type when considering both power density and energy density (Zhou et al., 2010), so it is largely used in a wide variety of industries including marine vessels (Ovrum and Bergh, 2015, Wen et al., 2016). In particular, Li-ion batteries are found excellent in power density (Kularatna, 2014, Song et al., 2019, Maheshwari et al., 2020). As a result, the case ship was modelled with Li-ion batteries for the onboard power system.

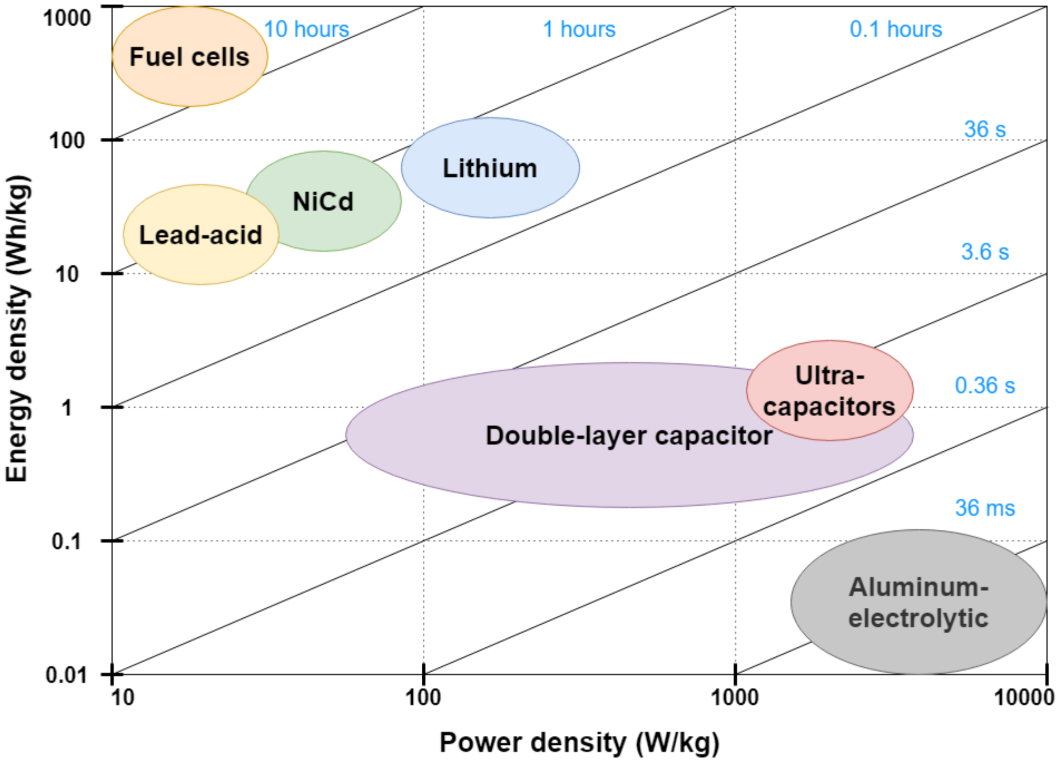


Figure 6-7. Power density and Energy density of energy storages (Kularatna, 2014)

Figure 6-8 (Buchmann, 2017) 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.

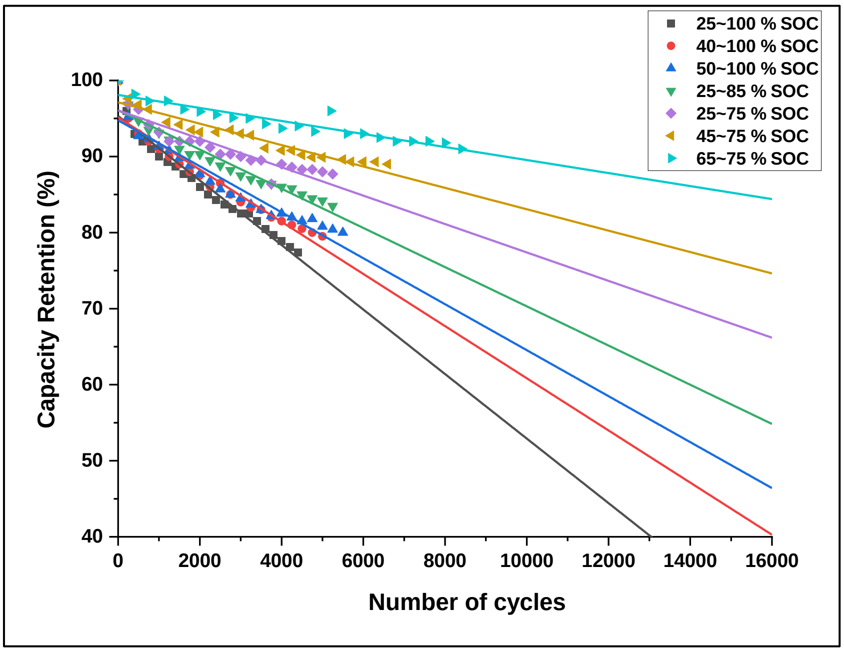


Figure 6-8. Actual capacity loss of battery by charging and discharging and expectation of battery life by extrapolation

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/m2 and 25 ℃. The amount of energy that can be generated by installed solar panels and varies with irradiance and temperature is shown in Figure 6-9.

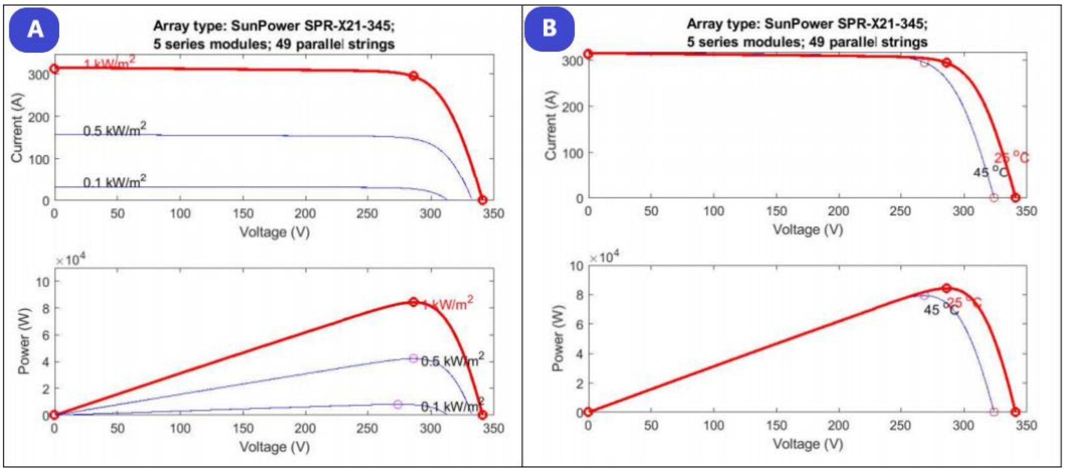


Figure 6-9. Maximum Current and Power graphs according to the voltage produced by installed solar panels; (A) Graphs according to irradiance at 25 ℃, (B) Graphs according to the temperature at 1000 W/m^2 irradiance

The critical drawback of the solar PV system is that the amount of energy produced varies significantly depending on whether conditions (Li et al., 2020, Wen et al., 2016). 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 6-10.

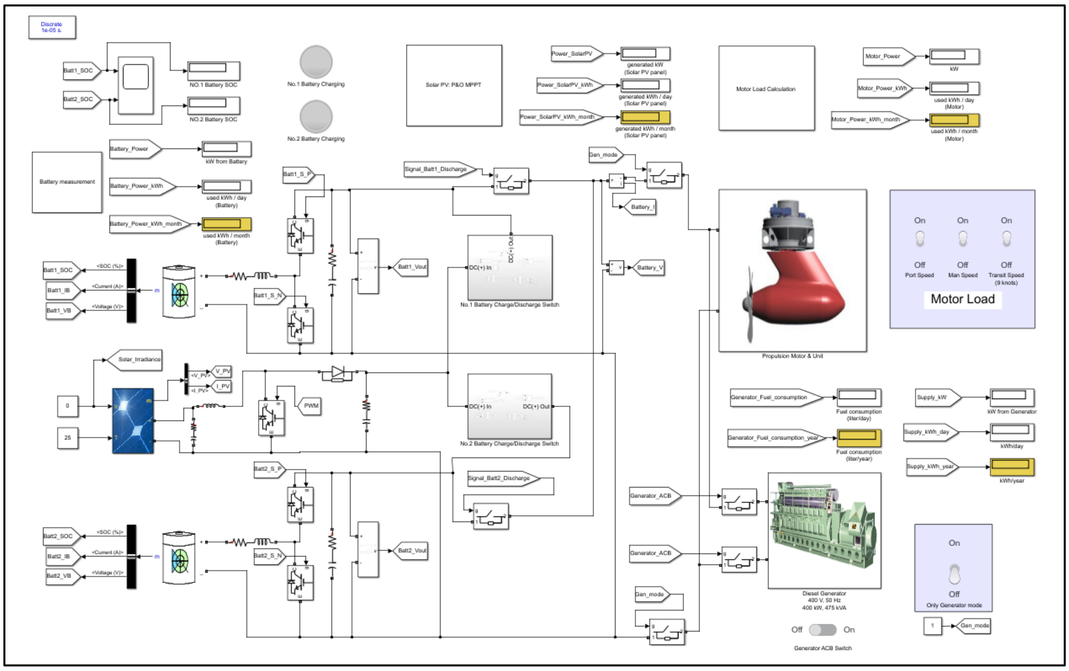


Figure 6-10. Modelling by using MATLAB/Simulink

(d) Simulation for each case

Each case discussed in the previous section can be presented in the simulation model as shown in Figure 6-6. The simulation was conducted based on 100 minutes of processing time, and various results of the entire operational process of the case ship were calculated based on the consistency of the simulation results.

In Case 1, marine gas oil (MGO), containing less than 0.1% sulphur, 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. (2019). 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 6-11 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.

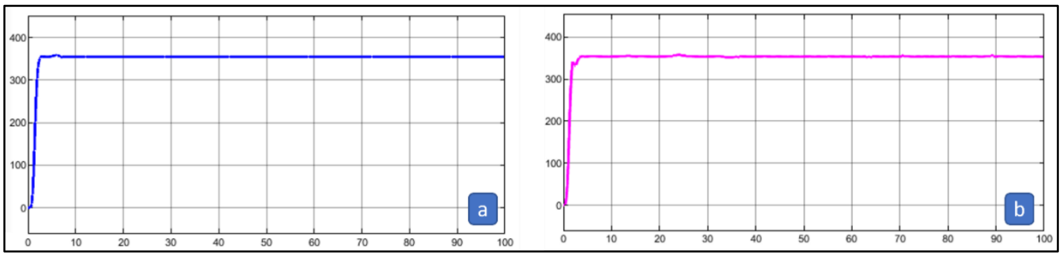


Figure 6-11. Simulation results from example of Case 1: (a) Power consumed by propulsion motor (kW), (b) Power generated by diesel generator (kW)

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 6-12 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.

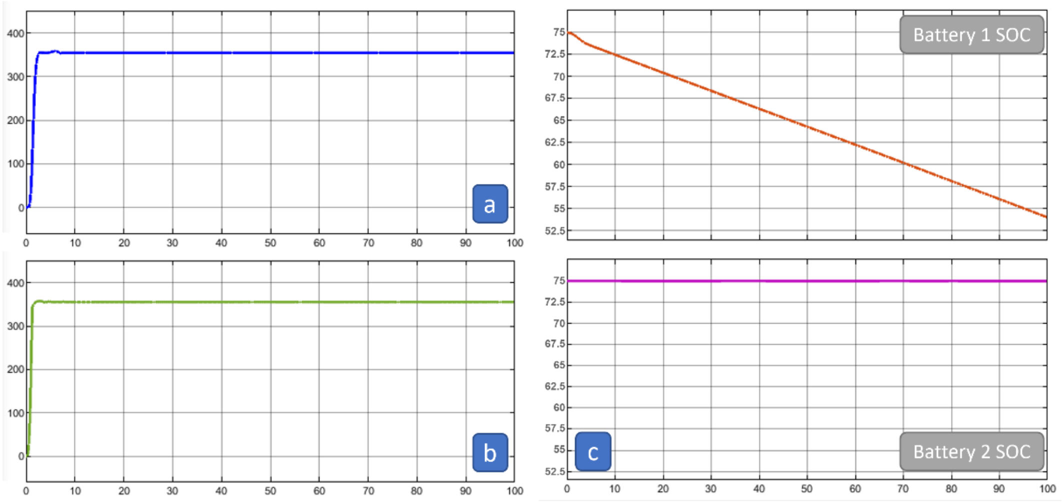


Figure 6-12. Simulation results based on simulation time of 100 hours from example of Case 2: (a) Power consumed by propulsion motor (kW), (b) Power supplied by battery (kW), (c) Battery SOC (Battery 1- Discharge mode, Battery 2- Charge mode)

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 6-13 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.

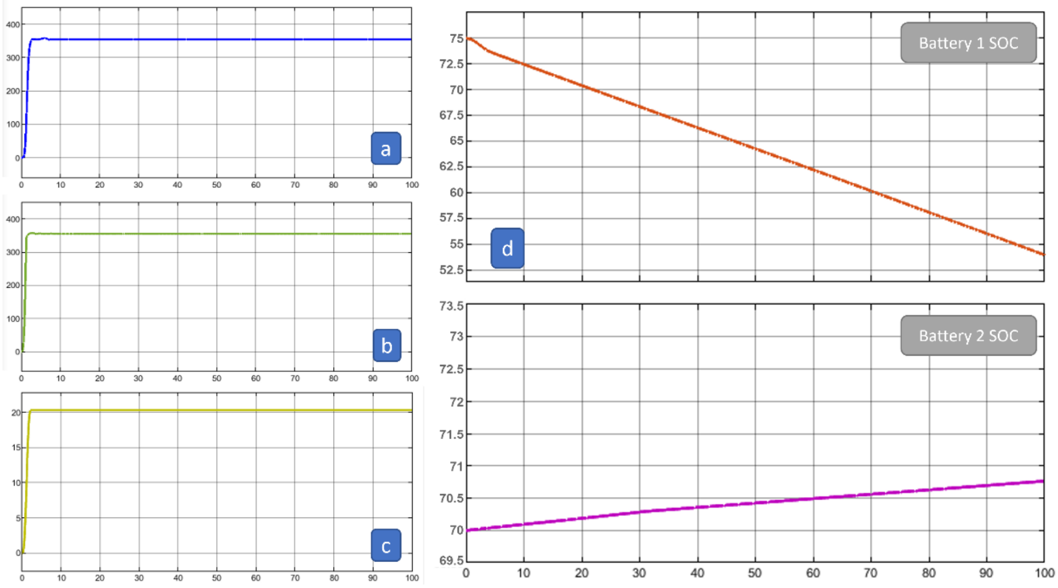


Figure 6-13. Simulation results based on simulation time of 100 hours from example of Case 3: (a) Power consumed by propulsion motor (kW), (b) Power supplied by battery (kW), (c) Power generated by solar panels (kW), (d) Battery SOC (Battery 1- Discharge mode, Battery 2- Charge mode)

6.2.4. *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, Characterisation, Normalisations, 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 generalisation 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, CO_2, CH_4, N_2O, SO_X, NO_X, PM and NMVOC (International Maritime Organization, 2020). Among several impact assessment methods to classify and characterise, CML (CML 2001) method is used in this thesis. 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 6-14. LCA is conducted by comparing the case applied with and without solar systems, and the benefits of utilising the electric propulsion ship applied with renewable sources are discussed through those results.

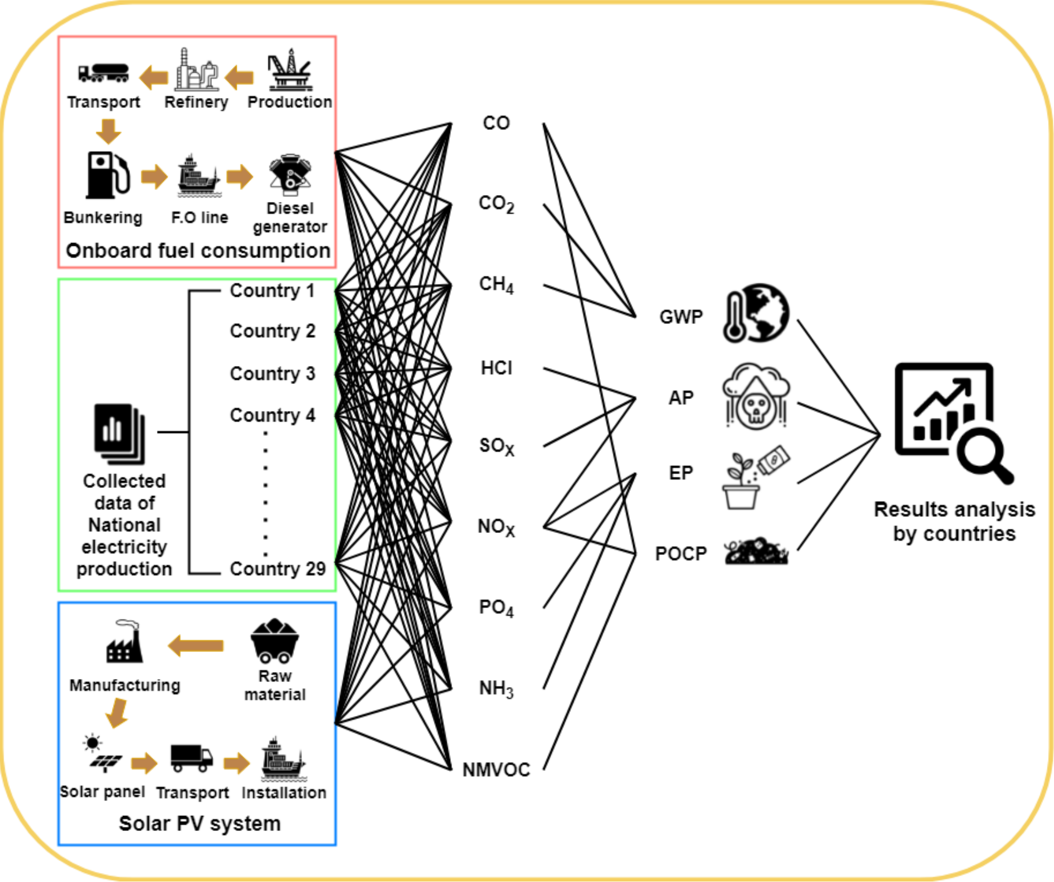


Figure 6-14. LCA procedure

6.2.5. 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.

6.3. Analysis results (Steps 4 and 5)

6.3.1. Case results

(a) 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 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 in Table 6-3 provided by Hwang et al. (2019) were applied for LCIA.

Table 6-3. 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 summarised in Figure 6-15. 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.

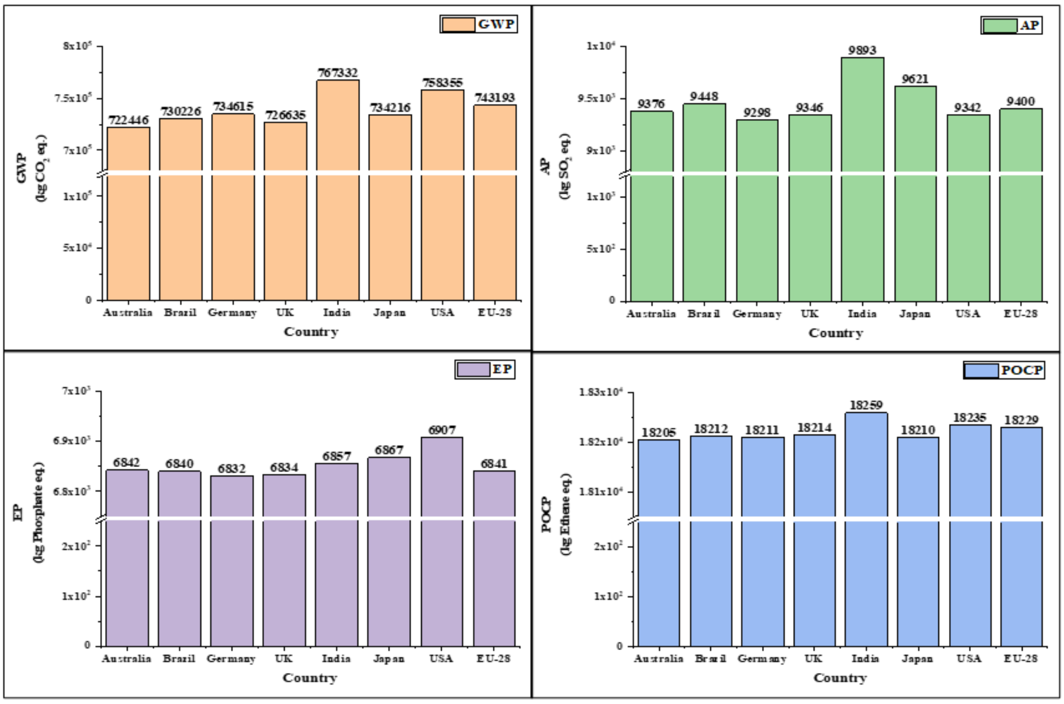


Figure 6-15. Results of case 1 by GWP, AP, EP and POCP

(b) 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 6-16 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.

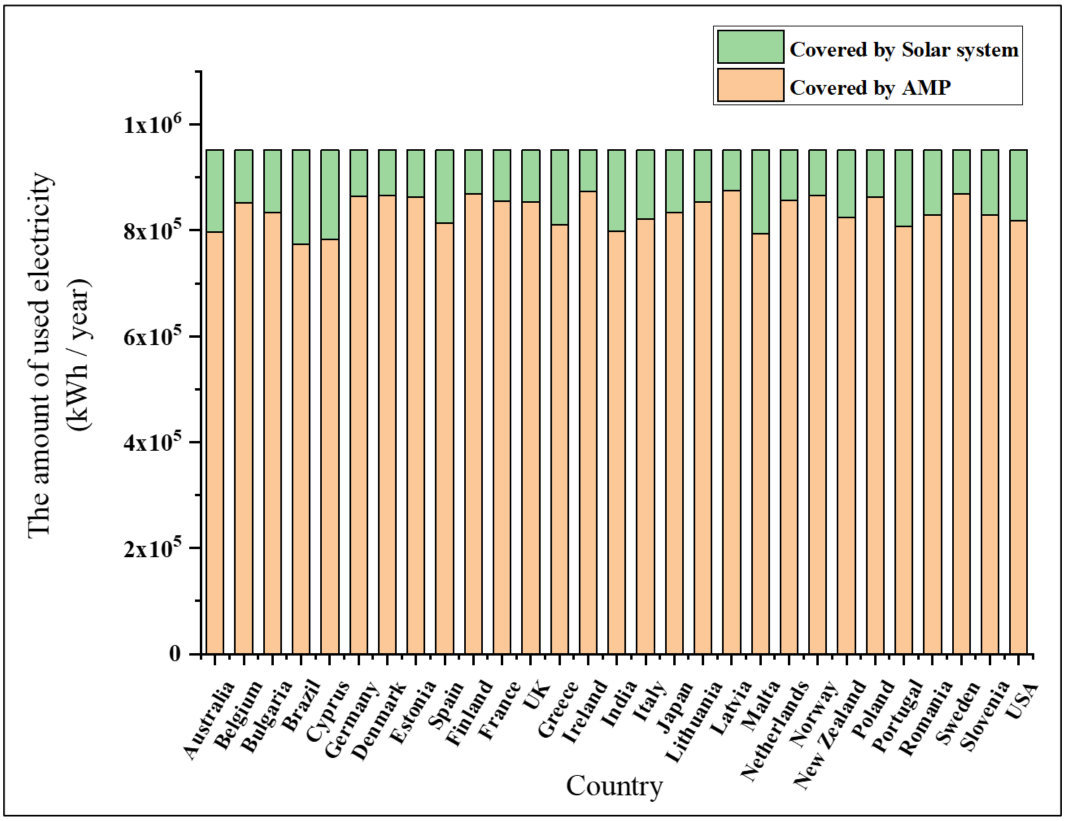


Figure 6-16. Case ship's electric power supply method by country

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.

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. (2020). Table 6-4 shows the functional units of solar PV system; unit environmental impact per 1 kWh electricity production from solar PV systems.

Table 6-4. 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 6-18 and Figure 6-19. 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 Table 6-5 shows, coal makes a greater contribution to GWP, compared to other energy sources. This trend can be clearly seen in Figure 6-17. The countries with high GWP values are evident of the high reliance on coal-based power generations (International Energy Agency (IEA), 2020b). 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.

Table 6-5. Emission factors of energy sources for generating electricity (Jeong et al., 2020)

	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}

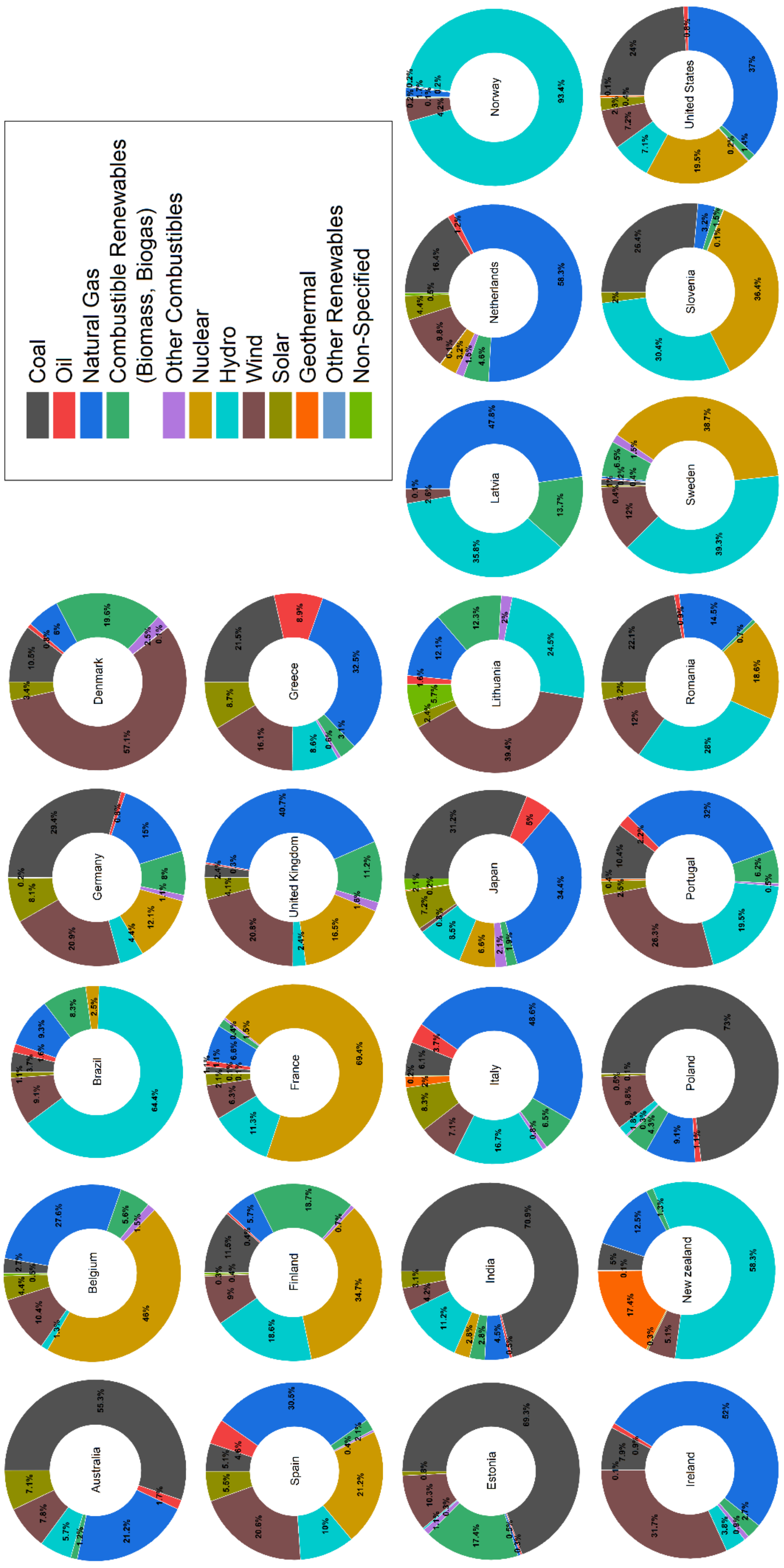


Figure 6-17. The proportion of resources used to generate national electricity in each country (International Energy Agency (IEA), 2020b)

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 6-4 and Table 6-5. 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).

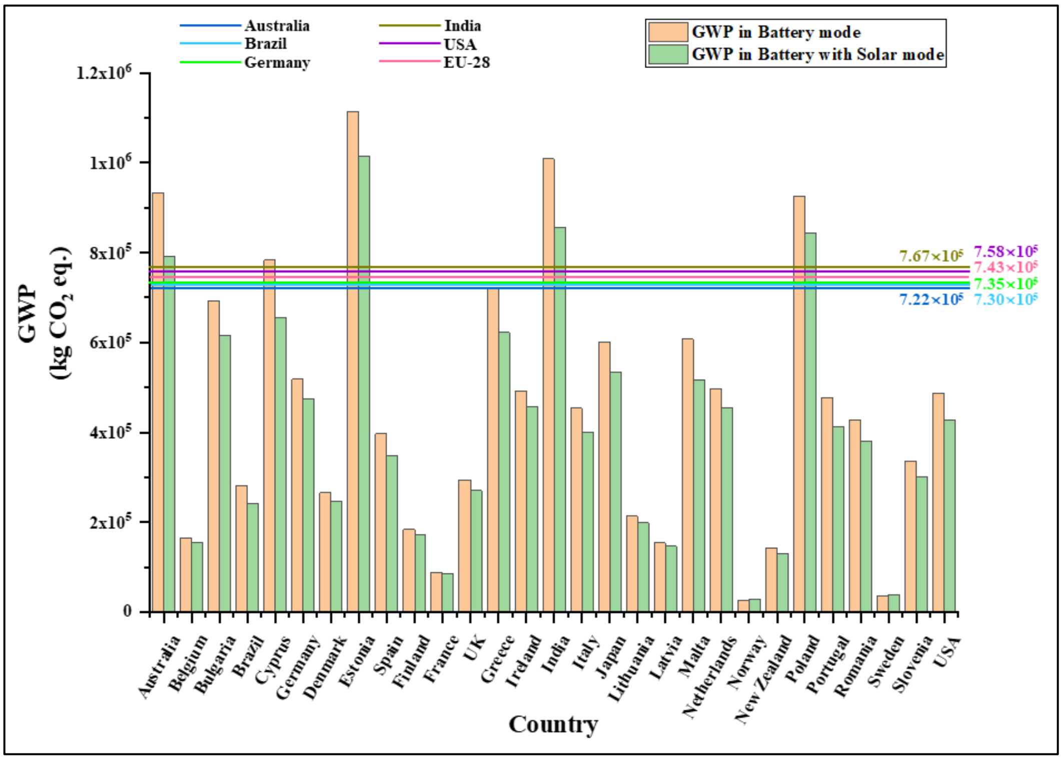


Figure 6-18. GWP values when 951,864 kWh is produced in each country with baselines from case 1

Results of Case 1 are used as baselines and those of Cases 2 and 3 were compared accordingly in Figure 6-18. 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.

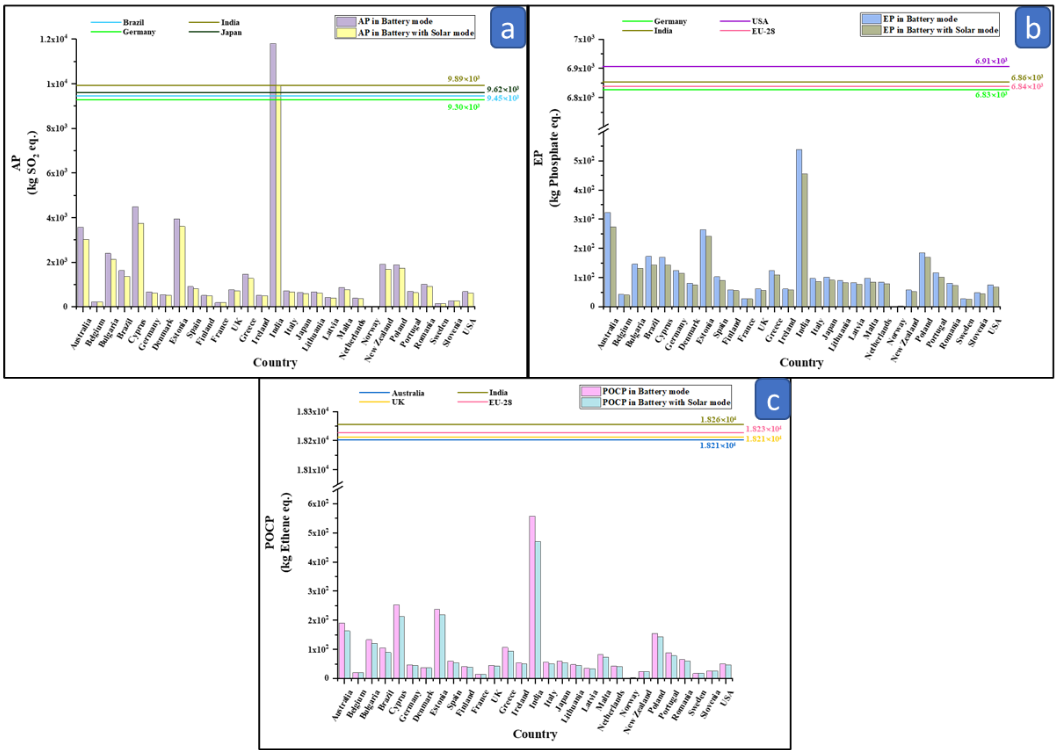


Figure 6-19. (a) AP, (b) EP and (c) POCP values when 951,864 kWh is produced in each country with baselines from case 1

As shown in Figure 6-19 (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 6-19 (b) and (c), India also shows remarkably high impacts, but the figures for all countries remain below the baselines.

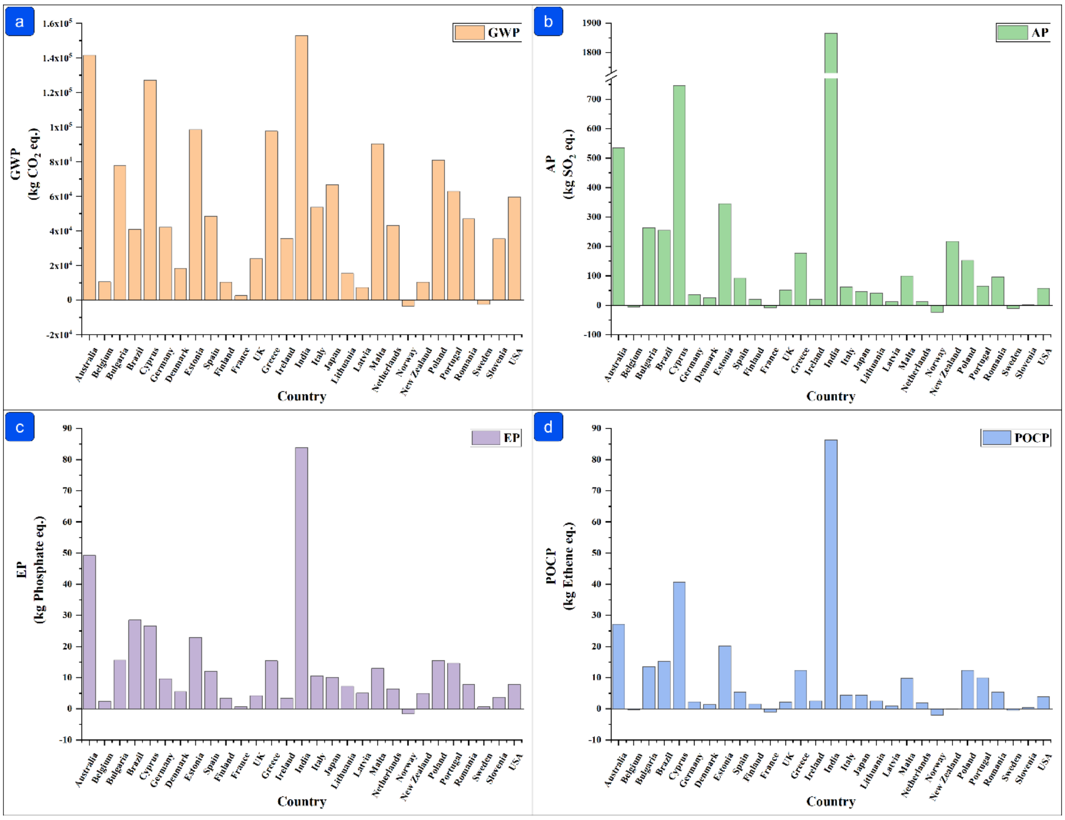


Figure 6-20. Differences of environmental impacts between Case 2 and Case 3

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 6-20. 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 thesis 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.

6.3.2. 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.

Therefore, the conventional LCA considers only the information of the installed solar panel, which is up to 84.525 kW at 1000 W/m2 and 25 ℃, regardless of the situation and the environment, replacing the data of power production as an assumption. 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 6-21 compares the results of the amount of electricity produced by solar panels obtained from the conventional LCA to those from LLCA.

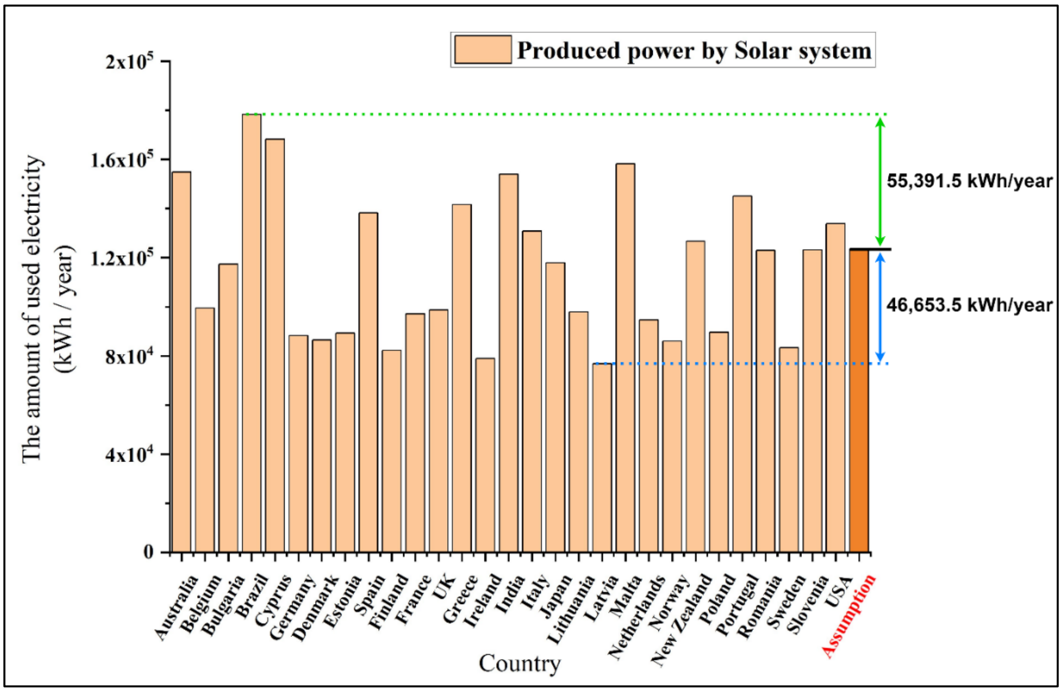


Figure 6-21. Amount of electricity produced by solar panels on the case ship by countries according to assumption and LLCA results

From Figure 6-21, 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 6-22 instead of the Live-LCA result in Figure 6-18 and Figure 6-19.

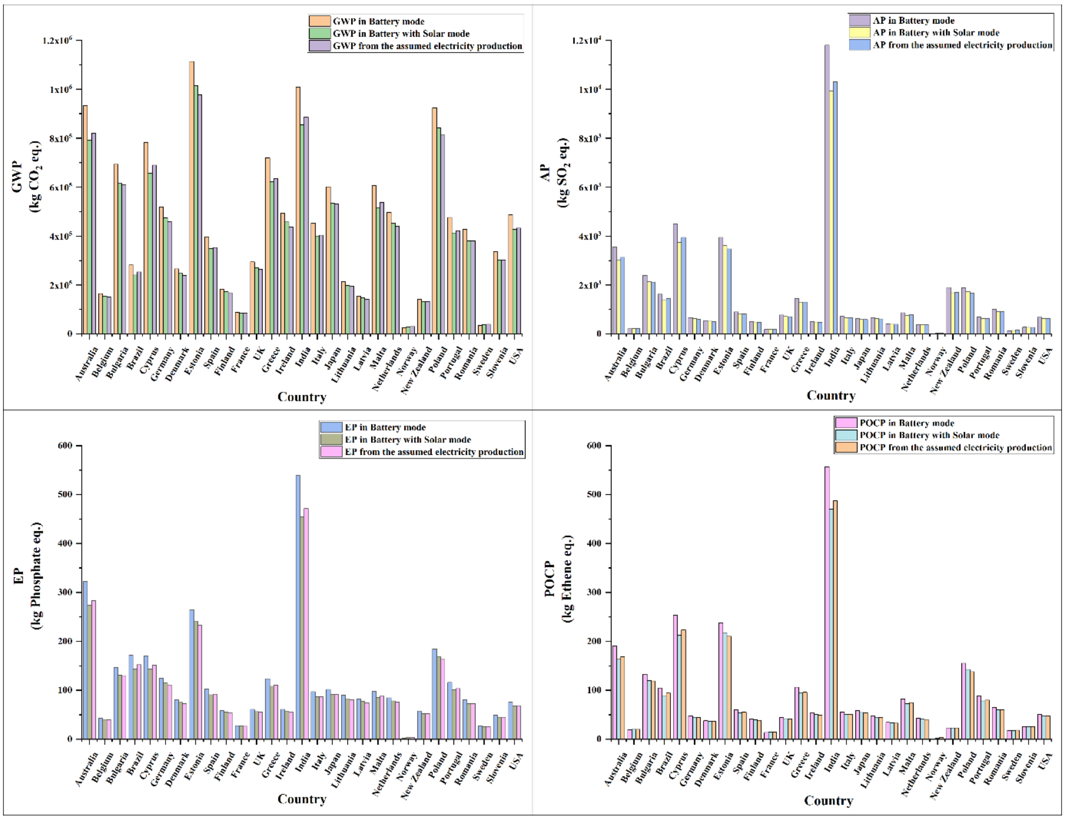


Figure 6-22. LCIA results by the country for Case 2, Case 3, and Case 3 assuming electricity production from solar panels

Figure 6-22 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 analysing 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 emphasised through this comparison that LLCA becomes an important methodology for more accurate LCA performance that complements the limitations of conventional LCA studies.

6.3.3. Functional unit of the Electric propulsion ship

In Table 6-6, 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 following 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 6-6 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 6-6. 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 6-7.

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 case study 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 thesis enables us to estimate the lifecycle environmental impacts of PV electric ships at any size.

Table 6-7. 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

6.4. Chapter summary and conclusions

This case study 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. From the holistic point of view, it improved the LCA study, which was case-specific, using fragmentary and limited data, to the L-LCA 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.

In fact, through the L-LCA methodology, it was identified that up to 44.5% more power was produced than expected from the amount of power produced through the solar PV system with the conventional LCA method, and the environmental impact was assessed. In essence, the LCA method used in the past approximated the amount of electricity produced by the solar panel based on its capacity, resulting in the exclusion of up to 44.5% of the energy produced from the study's findings. The Live-LCA technique, however, has demonstrated the possibility of conducting a more precise and dependable assessment by accurately deriving this previously unavailable data and conducting an environmental impact evaluation based on the actual situation.

Through it, this case study addressed the research gap highlighted in section 3.2.2 with regard to solar PV and generated insights into the fundamental question of whether electric propulsion ships can be considered eco-friendly in all countries and regions. The findings indicated that the answer to this question is not always affirmative, implying that there are limitations to the extent of environmental benefits derived from the replacement of fossil fuel-powered ships with electric propulsion ones.

In this study, the production and transportation of MGO were considered comprehensively in terms of LCA. When 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.

In terms of electrical energy, 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.

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/m^2 and 25 °C, 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.

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.

LCA results from this case study 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. In addition, the following requirement can be derived; As the environmental impact of electric propulsion ships depends heavily on the method of electric energy production and the power generation source, continuous discussions are necessary to identify ways of achieving an eco-friendly environment.

7. LIFECYCLE ENERGY SOLUTION OF THE ELECTRIC PROPULSION SHIP WITH L-LCA

Through the literature review in Chapter 3 and 4, it can be seen that the energy flow in the maritime sector has not been properly analysed to cover the entire life cycle from a holistic point of view. In other words, lots of parts are replaced by predictions or assumptions, which obscure an intuitive assessment of how much a ship's activities really affect the environment. As a result, it was not possible to suggest which fuel should be used in what way to become a true greener fuel in the shipping sector. These ambiguities and various challenges provided a strong motivation for conducting this case study and provided a fundamental question: ‘What are the promising energy solutions for the shipping sector?’.

Therefore, it can be confirmed that research that is able to resolve the ambiguity caused by predictions and assumptions, and in which various aspects mentioned are adequately considered is essential. This research gap can be overcome through the Live-LCA method and research methodology used in this thesis, and such kind of research can only provide the right energy solution to the shipping field.

7.1. Introduction

Carbon-free fuels are considered cleaner maritime energies, which are undoubtedly thought to bring the shipping industry towards a more 'green' and 'sustainable' business. However, in recent studies on life cycle assessment (LCA), Jang et al. (2021) and Jeong et al. (2018) argue that the use of these clean fuels is far from zero-emission while warning that those energies may dangerously misguide people to adverse outcomes when deconstructed without a proper understanding of their environmental benefits/harms. Therefore, it can be strongly argued that LCA research is absolutely necessary for the shipping field through results of these LCA studies. And then those can lead the vague decision making and policy direction setting that 'carbon-free fuel is the same as zero-emission' to the right direction.

This case study has been proposed to achieve the following objectives, which will reduce the aforementioned research gap and provide answers to fundamental questions.

- Present the criteria and rationale for applying alternative energy to the maritime sector
- Comprehensive coverage of various vessel activities and clear identification of ambiguous environmental impacts
- Identify the exact environmental impact of carbon-free fuel to be used as the next-generation fuel and provide easy-to-access environmental indicators through case studies
- Presenting a new paradigm for LCA research in the energy part of the maritime sector
- Presenting the energy investment and policy direction of the Maritime sector in the future

This part was conducted to satisfy the need to cover all these multifaceted considerations of alternative fuels, which are currently being actively studied. Eco-friendly alternative energy sources were analysed in consideration of all flows from production, transportation, storage, and use, and then compared with the existing fossil fuel. Thus, this compelling research can provide a better understanding of the issues associated with the use of these new alternative energy sources, and serve as a basis and evidence for confidently suggesting alternative fuel adoption in the shipping sector.

Furthermore, the Live-Lifecycle assessment technique was introduced to improve the uncertainty in which a significant portion of the existing LCA study was replaced by assumptions and guesses, and the reliability and accuracy of the study were greatly improved. This research method will complement the limitations of current LCA research and will serve as a guide to more accurately assess environmental impacts in future research in the shipping field.

It was also expected that the findings of this study will incentivise investment in a range of optimal solutions for decarbonising shipping to provide significant commercial opportunities across all energy options considered to be the most competitive. Moreover, it can directly suggest the future direction to the naval architects, shipyards and shipowners from a holistic environmental point of view.

7.2. Outline of the case study

Figure 7-1 is a schematic representation of the outline for this study. As a case study, the lifecycle comparative analysis was conducted on the viability of three zero-carbon fuels, ammonia, hydrogen, and inland electricity compared to MGO, based on the Well-to-Wake environmental impacts and technical availability. In addition, it was conducted based in Scotland, and the data was collected from actual ferries operated there by Caledonian Maritime Assets Limited (CMAL).

In Task 1, projection of the Scotland energy pathways for Ammonia, Hydrogen, Electricity and diesel was planned and conducted. To determine the optimal energy solutions, all credible scenarios for the upstream pathways for those fuels were developed, based on the current and future prospected UK energy infrastructure. Those scenarios were proposed to be examined for West-Scotland shipping and extended to the UK and international targets through other Tasks.

Identification of credible business scenarios for designing/operating zero-carbon fuelled ferries and bunkering operations was performed in Task 2. It begins by identifying the issues faced by the ferries' operator at present time and developing appropriate scenarios relative to the design and operation of zero-carbon fuelled ships. Those scenarios were determined based on the operator's current fleet operation plans and were used for the comprehensive assessment proposed in the following task. In particular, it was assumed that all 27 ferries would transition to 10 different power source options utilising the electric propulsion system in Task 2. This was done to accurately assess the environmental impact of the fuels selected in the case study in comparison to fossil fuels.

The main content of Task 3 is the presentation of the life cycle environmental impacts of zero-carbon fuels for case ferries. LCA was applied to determine the holistic prospect and benefits of using zero-carbon fuels in the UK environment under the scenarios in Tasks 1 and 2 from raw material acquisition through production and use to the end-of-life treatment, recycling and final disposal. Especially, the Live-LCA methodology which was initially proposed in section 5.2 to remedy the inherent shortcomings of conventional LCA was adopted to increase the reliability and accuracy of the assessment results.

Lastly, Task 4 is composed of roadmap development for alternative fuels for UK shipping and dissemination of findings to public/stakeholders. As an extension of Task 3, this task was proposed to provide meaningful guidance for UK's successful zero-carbon shipping, by proposing the recommended practice and strategies for the actual operator as the end beneficiary. It was also to present quantitative impacts on the UK economy and environmental protection. An enhanced LCA method was applied to offer scale-up information to obtain the roadmap for the future UK zero-carbon business.

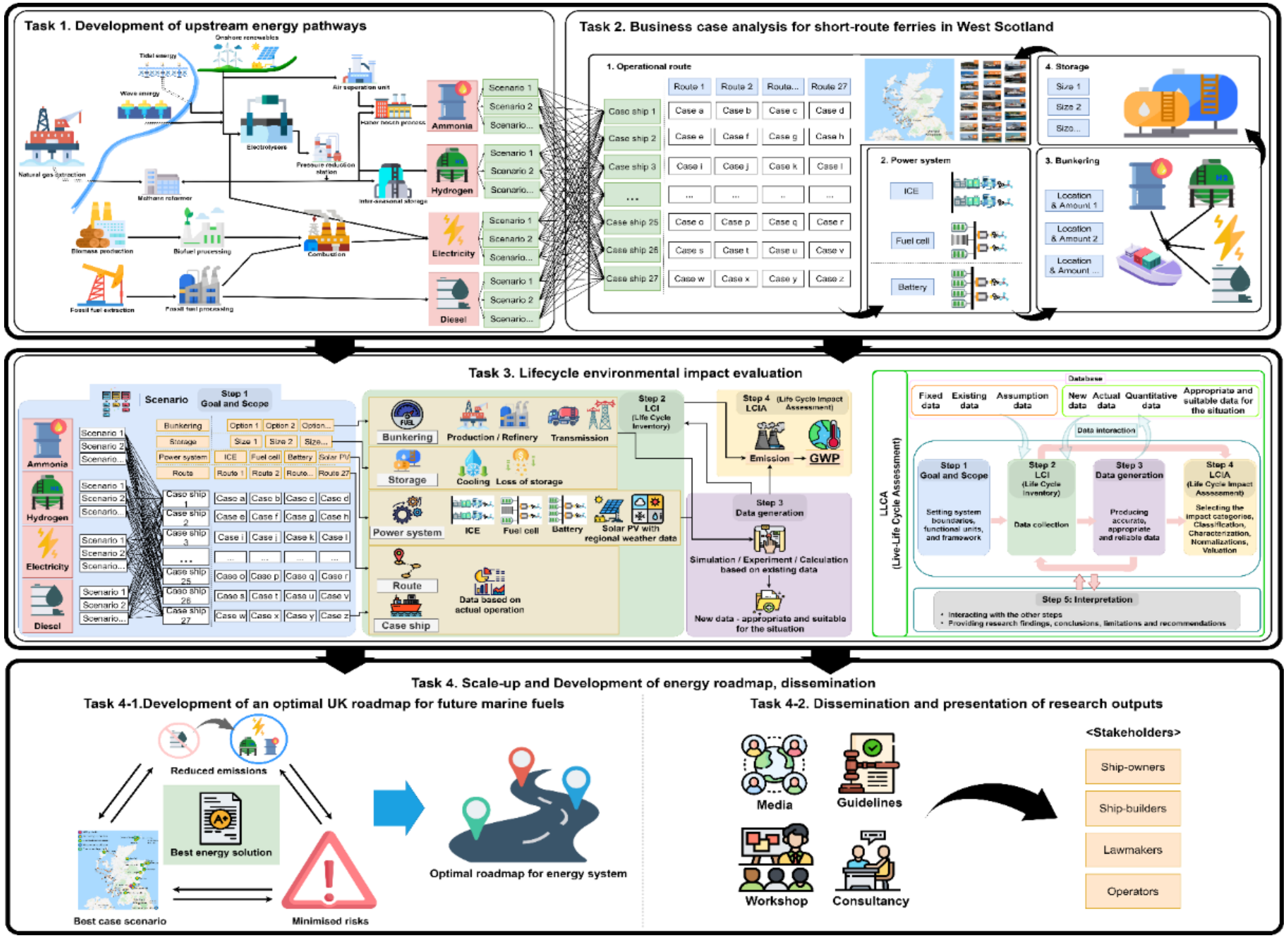


Figure 7-1. Case study outline

7.3. Task 1: Development of upstream energy pathways

7.3.1. Data collection for energy pathways

This was a part of the fundamental task of collecting, classifying, and organising the vast and diverse data required for this study. This task was focused on collecting data for energy infrastructures across Scotland and the UK from works of literature and public data sources. As a result, it was obtained the upstream data associated with hydrogen, ammonia, electricity and diesel productions and supply chains and onboard bunkering.

7.3.2. Development of energy pathways

While carbon-free fuels are in the early stages of development in the UK, there are various views on how these fuels can be produced, distributed, and used onboard for the clean shipping economy. It has been developed the energy pathways of ammonia, hydrogen, electricity and diesel and identified that the lifecycle impacts of those fuels are highly dependent on their primary energy sources, production methods, distribution as well as onboard usage which will lead to remarkable distinctions in the UK economy and environment. To determine the optimal energy solutions, all credible scenarios for the upstream pathways for these fuels were developed, based on the current and future prospected UK energy infrastructure and grids. Those scenarios were used as key inputs for Tasks 3 and 4 (section 7.5 and 7.6).

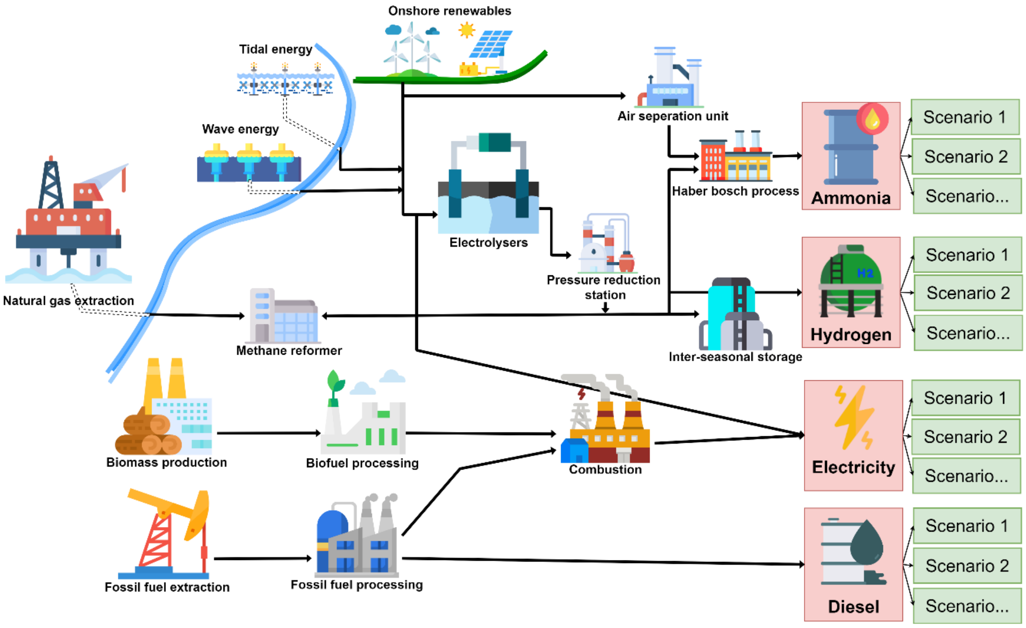


Figure 7-2. Credible energy pathways for the maritime industry

Figure 7-2 shows the various production processes of the proposed energy sources in this study. In this figure, Diesel represents Marine gas oil (MGO) with 0.1% sulphur content. For hydrogen and ammonia, depending on production methods, green/blue hydrogen and ammonia were considered, respectively. It was found that there was no production of grey ammonia and hydrogen in Scotland.

Six primary energy sources were considered for electricity generation/supply: coal, oil, natural gas, nuclear, hydro, and wind. In addition to this, raw material shares of the UK electrical energy production in 2019 were taken into account; at the rate of coal 2.4%, oil 0.3%, natural gas 40.7%, combustible 11.2%. other combustibles 1.6%, nuclear 16.5%, hydro 2.4%, wind 20.8%, solar 4.1% was also considered (International Energy Agency (IEA), 2020b).

Table 7-1. Selected fuel production areas and each distance to bunkering points for the case ships (Unit: km)

Energy production			Case Ship																										
Produce area	Local name	Type	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
			MV Isle of Cumbrae	MV Argyle	MV Bute	MV Loch Dunvegan	MV Loch Shira	MV Caledonian Isles	MV Isle of Arran	MV Catriona	MV Loch Ranza	MV Hebridean Isles	MV Finlaggan	MV Clansman (a)	MV Coruisk	MV Loch invar	MV Loch Tarbert	MV Loch Buie	MV Loch Striven	MV Clansman (b)	MV Isle of Lewis	MV Loch Fyne	MV Lord of the Isles	MV Hallaig	MV Loch Alainn	MV Hebrides	MV Loch Portain	MV Loch Seaforth	MV Loch Nevis
MGO-1	Grangemouth	0.1% Sulphur	181	98.2	98.2	171	103	106	106	216	230	207	207	163	163	216	213	237	163	163	163	247	247	333	317	378	445	342	247
H_2 -1	St Fergus	Blue	407	354	354	398	350	356	356	399	434	412	412	335	335	323	359	397	321	335	335	326	326	331	489	376	443	260	326
H_2 -2	Orkney	Green	536	528	528	526	560	541	541	512	524	502	502	415	415	404	439	477	401	415	415	406	406	368	542	413	430	259	406
H_2 -3	Orkney	Green	545	538	538	536	570	551	551	520	534	511	511	425	425	414	448	487	410	425	425	416	416	378	552	423	440	269	416
H_2 -4	St Fergus	Green	405	351	351	396	348	354	354	396	431	409	409	336	336	321	360	398	322	336	336	320	320	332	490	377	444	261	320
H_2 -5	Grangemouth	Blue	178	97.4	97.4	169	96	99.8	99.8	144	227	205	205	160	160	214	210	233	160	160	160	244	244	358	314	403	471	338	244
H_2 -6	Whitelee windfarm	Green	164	54	54	155	44	42.9	42.9	88.1	214	190	190	171	171	229	226	250	171	171	171	261	261	346	331	391	459	389	261
H_2 -7	Leven	Green	233	152	152	223	150	154	154	199	271	249	249	195	195	247	245	268	195	195	195	273	273	334	349	379	447	315	273
H_2 -8	Stornoway	Green	424	491	491	458	502	504	483	440	454	431	431	344	328	316	300	385	330	344	233	199	194	152	204	107	94.4	8.8	208
H_2 -9	Dundee	Green	236	176	176	227	181	185	185	230	264	242	242	188	188	240	237	261	188	188	188	266	266	328	342	373	440	298	266
H_2 -10	Aberdeen	Green	342	288	288	319	286	290	290	335	370	347	347	294	294	312	340	366	294	294	294	299	299	326	447	371	438	256	299
H_2 -11	Aberdeenshire	Green	386	332	332	376	331	334	334	379	414	391	391	311	311	304	335	373	297	311	311	302	302	319	465	364	431	245	302
H_2 -12	Newfield	Green	342	339	339	333	348	370	370	317	333	308	308	221	221	213	248	286	210	221	221	186	186	177	349	223	284	106	186
H_2 -13	Glensaugh	Green	299	239	239	276	244	247	247	293	327	305	305	250	250	298	300	324	250	250	250	291	291	321	399	366	433	250	291
NH_3 -1	Orkney	Green	547	542	542	538	573	576	576	522	536	514	514	427	427	420	451	489	413	427	427	418	418	381	554	426	443	265	418
NH_3 -2	Saltend Chemicl as Park	Blue	572	481	481	506	480	483	483	528	621	599	599	585	585	638	635	659	585	585	585	670	670	793	747	839	906	774	670

Note: H_2-8 (Outer Hebrides Local Energy Hub (OHLEH)); Mainly for the local supply (Local Energy Scotland, [accessed 6 March 2022]), H_2-11; Hydrogen will be supplied from 2030.

Figure 7-3 displays 13 pathways to produce hydrogen. According to the method of producing hydrogen, it is divided into blue hydrogen and green hydrogen. Green hydrogen means hydrogen with almost no carbon emission using renewable energy such as solar PV, wind, and biogas. In this study, it was assumed that green hydrogen would be supplied to case ships from a total of 11 production sites. On the other hand, it was confirmed that two locations in Scotland would produce blue hydrogen. Unlike green hydrogen, blue hydrogen emits GHG while producing hydrogen through natural gas, but it can still achieve carbon neutrality by absorbing and storing GHG generated in the production process through Carbon Capture Utilisation and Storage (CCUS) systems.

Ammonia production relies on an abundant supply of energy, mainly natural gas. Alternatively, by electrolysis of water (or steam) to produce hydrogen using zero-emission methane pyrolysis or by utilising zero-carbon electricity from renewable energy sources or nuclear power. Ammonia, like hydrogen, is divided into green ammonia and blue ammonia according to the production method. In this study, one green ammonia production site in Scotland and one blue ammonia production site in England were identified. Then, all credible scenarios of the ammonia supply chain to ships from those production sites were considered for the follow-up analysis.

Grangemouth refinery was selected for the production area of MGO currently used on ships along with hydrogen and ammonia.

Table 7-1 shows that production sites of hydrogen (13), ammonia (2), and MGO (1) were applied to the 27 case ships and the distances from the production sites to individual ships as well as transport means with their emissions were estimated. The total amount of fuels supplied to the case ships was determined by the estimates of onboard fuel consumption in consideration of their current operating profiles.

7.4. Task 2: Business case analysis for ferries

7.4.1. Ferry routes analysis

Data/information on the selected 27 ferries on 26 routes was collected and used for developing business cases. In addition to this data/information, in order to conduct research on electric-powered ships that would use hydrogen and ammonia as fuel, identified information of production sites in Task 1 was evaluated together. Together with Table 7-1, Figure 7-3 below is a summary of this task that represents 26 fleet operation routes by 27 ferries, with 1 MGO-producing site, 13 hydrogen-producing sites, and 2 ammonia-producing sites in Scotland and England. Finally, service routes and specification of ferries are listed up in Table 7-2.

Figure 7-3. The projection of ferries' operating routes and availability of energy sources for the Scotland ferries

Table 7-2. Service routes and ferries' specification

Service route	Ship No.	Regular vessel(s)	Mainland or inner port	Island or outer port	Voyage time (hours)	Daily round trips	Total propulsion power (kW)	Ship Length (m)	Ship Breadth (m)	Power consumption (kWh/year)
1	1	MV Isle of Cumbrae	Portavadie, Cowal	Tarbert, Kintyre Peninsula	0.42	12	380	32	10	1,361,450
2	2	MV Argyle	Wemyss Bay, Inverclyde	Rothesay, Isle of Bute	0.58	8	2,696	72	15	8,147,384
	3	MV Bute	Wemyss Bay, Inverclyde	Rothesay, Isle of Bute	0.58	8	2,696	72	15	8,147,384
3	4	MV Loch Dunvegan	Colintraive, Cowal	Rhubodach, Northern Bute	0.08	32	659	54.2	13	1,187,759
4	5	MV Loch Shira	Largs, North Ayrshire	Cumbrae Slip, Isle of Cumbrae	0.17	28	1,100	53.9	13.9	3,355,567
5	6	MV Caledonian Isles	Ardrossan, North Ayrshire	Brodick, Isle of Arran	0.92	5	4,320	94	15.8	12,620,483
6	7	MV Isle of Arran	Ardrossan	Campbeltown, Kintyre	2.67	1	3,450	84.92	16	5,903,267
7	8	MV Catriona	Tarbert, Kintyre Peninsula	Lochranza, Isle of Arran	1.90	4	750	43.5	12.2	3,814,250
8	9	MV Loch Ranza	Tayinloan, Western Kintyre	Ardminish, Isle of Gigha	0.33	11	540	30.2	10	1,362,423
9	10	MV Hebridean Isles	Kennacraig, Western Kintyre	Port Ellen, Southern Islay	2.33	2	3,450	85.15	15.8	10,330,717
10	11	MV Finlaggan	Kennacraig	Port Askaig, Eastern Islay	2.08	2	8,000	89.8	16.3	20,987,500
11	12	MV Clansman (a)	Oban	Scalasaig, Colonsay	2.33	1	7,680	99	15.8	11,289,693
12	13	MV Coruisk	Oban	Craignure, Isle of Mull	0.77	10	2,280	65	14	11,406,007
13	14	MV Lochinvar	Lochaline, Morvern Peninsula	Fishnish, Mull	0.25	14	750	43.5	12.2	1,756,563
14	15	MV Loch Tarbert	Kilchoan, Ardnamurchan Peninsula	Tobermory, Mull	0.58	13	540	30	10	2,817,739
15	16	MV Loch Buie	Fionnphort, Ross of Mull	Iona	0.17	48	540	30.2	10	2,972,560

16	17	MV Loch Striven	Oban	Achnacroish, Isle of Lismore	0.83	9	540	30.2	10	2,786,775
17	18	MV Clansman (b)	Oban	Isle of Coll andTiree	3.33	2	7,680	99	15.8	32,256,267
18	19	MV Isle of Lewis	Oban	Castlebay, Isle of Barra	5.00	1	6520	101.25	18.52	20,593,300
19	20	MV Loch Fyne	Mallaig	Armadale, Sleat Peninsula, Skye	0.42	5	659	54.2	13.2	927,936
20	21	MV Lord of the Isles	Mallaig	Lochboisdale, South Uist	3.25	2	5320	84.6	15.8	21,931,390
21	22	MV Hallaig	Sconser, Skye	Raasay	0.25	32	750	43.5	12.2	4,015,000
22	23	MV Loch Alainn	Ardmhor (Barra)	Isle of Eriskay	0.67	12	970	41	13.4	5,107,080
23	24	MV Hebrides	Uig, Skye	Lochmaddy, North Uist	1.75	4	7680	99	15.8	33,869,080
24	25	MV Loch Portain	Leverburgh, Harris	Isle of Berneray	1.00	8	2120	49	14.4	11,107,680
25	26	MV Loch Seaforth	Ullapool, Wester Ross	Stornoway, Lewis	2.75	2	8000	117.9	18.4	27,703,500
26	27	MV Loch Nevis	Mallaig	small isles Eigg Muck Rhum Canna	4.08	1	2266	49	11.4	6,034,536

7.4.2. Ship design scenarios

This task was begun by identifying the issues faced by the maritime sector in terms of reducing GHG emissions at present time and developing appropriate scenarios relative to the design and operation of zero-carbon energy fuelled ships. Credible scenarios were determined based on the current fleet operation, and they were used for the comprehensive assessment proposed in Task 3.

Based on the scenario of changing the existing ferries to electric propulsion ships and the energy sources considered in the 'Task 1 Energy pathway', a total of 10 types of vessels were conceived as follows in Table 7-3 and Figure 7-4.

Table 7-3. 10 scenario options for the design of case ships

Type	The power source of the electric propulsion ship	Fuel
1	Diesel generator (ICE)	Diesel (MGO)
2-1	Hybrid ship (Diesel engine (main) + Battery (sub))	Diesel (MGO) + Electricity
2-2	Hybrid ship (Diesel engine (50%) + Battery (50%))	
2-3	Hybrid ship (Diesel engine (sub) + Battery (main))	
3	Full battery	Electricity
4	Battery + Solar PV system	Electricity
5	Hydrogen fuel cell	Hydrogen
6-1	Hydrogen fuel cell (main) + Battery (sub)	Hydrogen + Electricity
6-2	Hydrogen fuel cell (50%) + Battery (50%)	
6-3	Hydrogen fuel cell (sub) + Battery (main)	
7-1	Hydrogen fuel cell (main) + Battery (sub) + Solar PV system	Hydrogen + Electricity
7-2	Hydrogen fuel cell (50%) + Battery (50%) +Solar PV system	
7-3	Hydrogen fuel cell (sub) + Battery (main) + Solar PV system	
8	Ammonia fuelled hydrogen fuel cell	Ammonia
9-1	Ammonia fuelled hydrogen fuel cell (main) + Battery (sub)	Ammonia + Electricity
9-2	Ammonia fuelled hydrogen fuel cell (50%) + Battery (50%)	

9-3	Ammonia fuelled hydrogen fuel cell (sub) + Battery (main)	
10-1	Ammonia fuelled hydrogen fuel cell (main) + Battery (sub) + Solar PV system	Ammonia + Electricity
10-2	Ammonia fuelled hydrogen fuel cell (50%) + Battery (50%) + Solar PV system	
10-3	Ammonia fuelled hydrogen fuel cell (sub) + Battery (main) + Solar PV system	

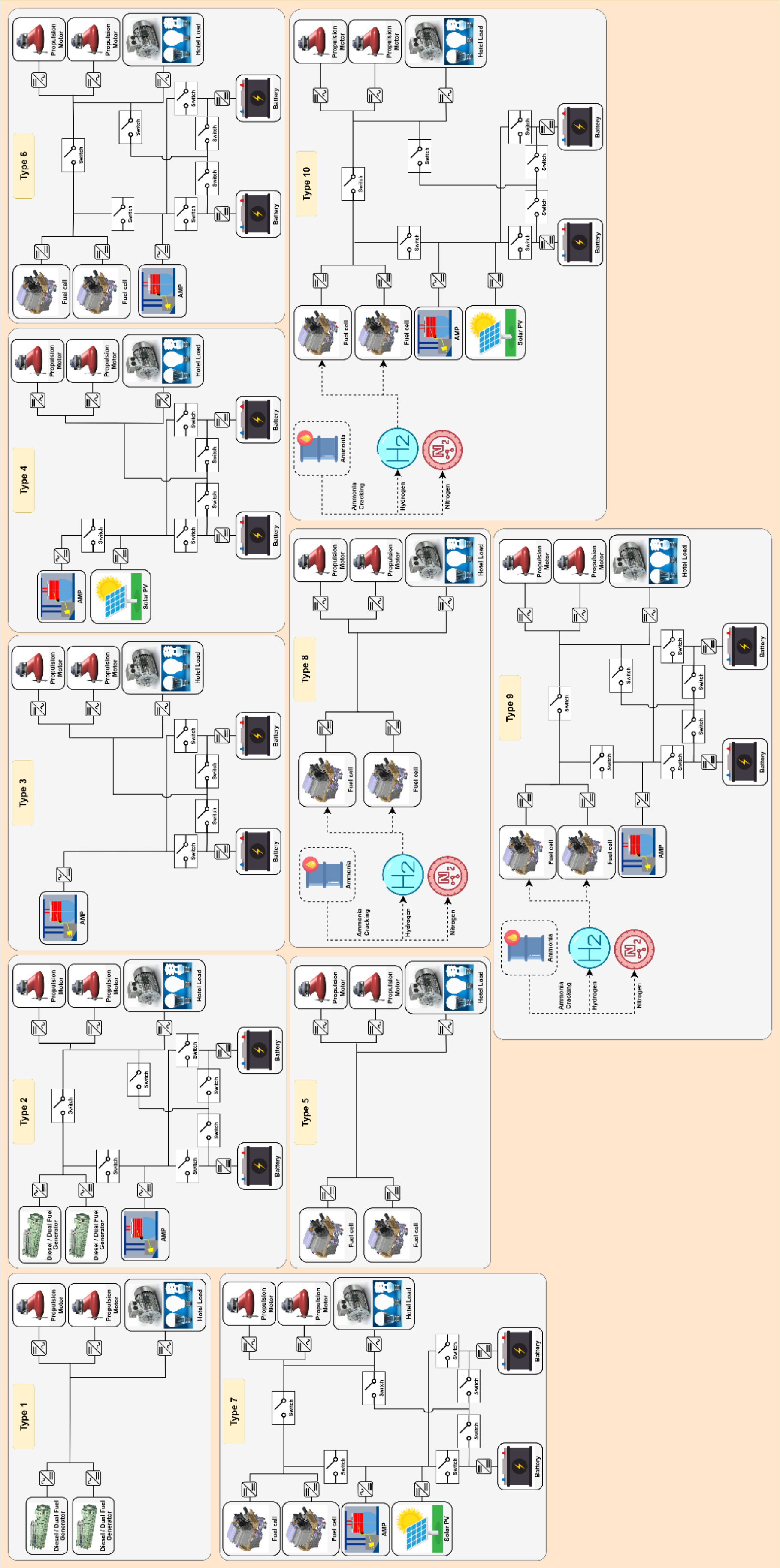


Figure 7-4. The conceptual diagrams for ship design

The AC power system has been widely used for almost all ships for the reason that diesel generators onboard produce AC power guaranteeing simple voltage conversion with the high technological maturity of safety devices such as circuit breakers. However, with the advancement of power electronics, DC distribution power systems have reached a level where they can be used in various fields (Jovcic et al., 2011). Thus, recently, the DC power distribution is being adopted as the power distribution method of more and more ships for reasons of high efficiency, excellent energy-saving at low load, reduced equipment footprint and increased installation flexibility, easy synchronisation between power sources, and the applied eco-friend power generation devices such as fuel cells and solar panels (Geertsma et al., 2017a, Kanellos et al., 2015, Tessarolo et al., 2013, Haseltalab and Negenborn, 2019).

Based on these advantages, the ship design scenarios in this study were proposed with the DC grid applied.

1) Type 1: Electric propulsion ship with Diesel generator engine

For Type 1, the electric energy to propel ferries and hotel load is produced by the Diesel generator engine using Marine Gas Oil (MGO) containing 0.1% sulphur considering emission regulation. In this type, the propulsion method is only considered to be changed from the existing main engines to the electric propulsion with the electric motors. Since the existing internal combustion engines are still under use, the overall ship propulsion system would remain very similar to the original type. Hence, the power system consists of the Diesel generator for electric energy production, the AC/DC converter to send the electricity produced by the generator to the DC grid, and the DC/AC converter to send power from the DC grid to the propulsion motor using AC power.

2) Type 2: Electric propulsion ship with Hybrid power sources

In Type 2, the electricity for propulsion and hotel load is either generated by a set of Diesel generators or supplied from the battery charged by

Alternative Maritime Power (AMP). The capacity of the generator and the battery installed onboard is not identical but depends on the power requirements of generators. The environmental impact would be affected by this design variation. Therefore, the optimal design considering various operating conditions is necessary to confirm and improve the ecological impact. Given this, the Type 2 concept was divided into three sub-types. In Type 2-1, diesel generators would be responsible for propulsion and battery would be for hotel load, whereas Type 2-2 was proposed to make diesel generators and battery share the equal electric load of 50% and Type 2-3 would be opposite to Type 2-1 so that diesel generators would cover hotel load and the battery would be in charge of propulsion load. The size of generators and batteries were determined differently to meet those operating conditions accordingly.

The Lithium-ion (Li-ion) battery type, most commonly used with a high density of energy and power as Energy Storage System (ESS) (Perčić et al., 2022), was assumed to be applied for the case ships.

This type of power system consists of the Diesel generator for electric energy production, the AC/DC converter to send the electricity produced by the generator to the DC grid, the Battery that stores land power supplied through AMP, the AC/DC converter to transfer the electricity to the battery from AMP, the DC/DC converter for charging and discharging the battery, and the DC/AC converter to transfer power from the DC grid to the propulsion motor using AC power.

3) Type 3: Electric propulsion ship with Full battery

For Type 3, the electric energy for propulsion and hotel load is only supplied from the battery charged by AMP. The total power capacity of the battery would be identical to the original power capacity each ship has. As considered in Task 1, various primary energy resources such as coal, oil, LNG, nuclear, hydro, and wind can be used to produce electricity, and pollutants generated during electricity generation differ highly depending on which resource is used. The power system consists of the battery systems, the AC/DC converter to transmit the electricity to the battery through AMP, the DC/DC converter for charging and discharging the battery, and the DC/AC converter to supply power from the DC grid to the AC propulsion motors.

4) Type 4: Electric propulsion ship with Battery and Solar PV system

For Type 4, the electricity for both propulsion and hotel load is supplied from either battery charged by AMP or Solar Photovoltaic (PV) system. The amount of electricity produced by the solar panel varies according to solar irradiance and temperature. And then, that amount of generated electric energy affects the amount of charged electricity to the battery from AMP. The battery capacity was kept the same as that of Type 3 in consideration that the solar panel produces relatively small power and inconsistently. The power system is composed of the batteries, the AC/DC converter to send the electricity to the battery through AMP, the DC/DC converter for charging and discharging the battery, solar panels with the DC/DC converter, and the DC/AC converter to supply power from the DC grid to the AC propulsion motors.

5) Type 5: Electric propulsion ship with Hydrogen fuel cell

For Type 5, the electric energy for propulsion and hotel load is supplied by the hydrogen fuel cell. As with Type 1, the fuel cell capacity varies according to the amount of power required of the ship, and there is no emission assumed to be produced from the fuel cell on board.

On the other hand, there would be different levels of emission during the hydrogen production process, depending on production methods; whether using blue hydrogen or green hydrogen is important.

It was set that the case ships would adopt Proton-exchange membrane fuel cell (PEMFC) for hydrogen fuel cell application. PEMFC is mainly used for small and medium-sized ships and it can be miniaturised, and guarantee fast response, operability at low temperatures, easy thermal management, simple maintenance, high power densities and good transient performance (Wee, 2007, Rivarolo et al., 2020, van Biert et al., 2016). However, PEMFC is greatly sensitive to the ppm level of carbon monoxide, so that, highly pure hydrogen is required to be used as fuel. Therefore, additional hydrogen purification devices are needed (Rivarolo et al., 2020, Lan and Tao, 2014).

The power system comprises the fuel cells, the DC/DC converter for the fuel cell to adjust the output voltage to the proper level and make the volatile voltage level steady, and the DC/AC converter for the power supply from the DC grid to the AC propulsion motors.

6) Type 6: Electric propulsion ship with Hydrogen fuel cell and Battery

For Type 6, the electric energy for propulsion and hotel load is supplied by the hydrogen fuel cells as well as the batteries charged by AMP. In this type, the capacity of the fuel cell and the battery would be different depending on the power supplying ratio between the fuel cells and the batteries. Thus, the environmental impacts would vary depending on their operating scenarios.

To identify optimal operation, the Type 6 concept was divided into three sub-cases. Type 6-1 represents that the fuel cell covers full propulsion load, whereas batteries are in charge of hotel loads. Type 6-2 represents when both fuel cells and batteries contribute to 50% of the total load and Type 6-3 is the opposite of Type 6-1 so that fuel cells cover hotel loads and batteries supply electricity for propulsion.

The power system consists of the fuel cells, the DC/DC converter for the fuel cell to adjust the output voltage to the proper level and make the volatile voltage level steady, batteries, the AC/DC converters to supply the electricity to the batteries via AMP, the DC/DC converters for charging and discharging batteries, and the DC/AC converters to supply power from the DC grid to the AC propulsion motors.

7) Type 7: Electric propulsion ship with Hydrogen fuel cell, Battery, and Solar PV system

Type 7 can be described by Type 6 with solar panels which contribute to producing electricity for battery charge. Since the amount of electricity produced by solar panels varies greatly depending on the weather conditions, the battery capacity was kept the same as that of Type 6. However, the amount of power received from the AMP varies depending on the amount of electrical energy produced by the fuel cell and the solar panels, under the power management plan.

As with Type 6, Type 7 was divided into three parts, 7-1, 7-2, and 7-3, in the same way, to investigate the variations of environmental impacts according to the power supply ratios between the fuel cell and battery. The power system is comprised of fuel cells, DC/DC converters, batteries with AMP, AC/DC converters, solar panels and AC propulsion motors.

8) Type 8: Electric propulsion ship with Ammonia-fuelled Hydrogen fuel cell

In Type 8, the electric energy for propulsion and hotel load is supplied by the fuel cell fuelled by ammonia. Ammonia is currently drawing more attention to the marine industry as a very attractive hydrogen carrier (Cesaro et al., 2021). An ammonia cracker split ammonia into two substances: hydrogen and nitrogen. The hydrogen from the cracker is supplied to fuel cells for electricity generation. As with Type 5, there would be a big gap in the environmental impacts, depending on the case ships use either blue ammonia or green ammonia. This study has considered these two different cases accordingly.

The power system mainly consists of the ammonia reforming system to produce hydrogen by cracking ammonia, the fuel cells, the DC/DC converters, the DC/AC converters and AC propulsion motors.

9) Type 9: Electric propulsion ship with Ammonia-fuelled Hydrogen fuel cell and Battery

Type 9 can be defined as the battery system with AMP in addition to Type 8. Both fuel cells and batteries were designed to supply the electricity for propulsion and hotel loads. In this type, the capacity of the fuel cell and battery varies depending on the ratio of the energy production from the onboard fuel cells as any energy deficiency would be covered by the batteries.

To confirm the variations of environmental impacts under different operating conditions, the Type 9 concept was split into Type 9-1 (fuel cells cover propulsion load and batteries are for hotel load), Type 9-2 (50-50 % shared by fuel cells and batteries) and Type 9-3 (fuel cells cover hotel load and batteries are in charge of propulsion load).

The power system consists of the ammonia reforming system, the fuel cells, the DC/DC converters, the batteries with AMP, the AC/DC converters and AC propulsion motors.

10) Type 10: Electric propulsion ship with Ammonia-fuelled Hydrogen fuel cell, Battery, and Solar PV system

Type 10 is described with Type 9 plus solar systems so that the onboard batteries can be charged either from the AMP or the solar panels. Since the amount of electricity produced by solar panels varies greatly depending on the weather conditions, the battery installation capacity was kept the same as that of Type 9. However, the amount of ammonia consumption and power received from the AMP was estimated based on the calculation of electricity generation by solar panels.

Regarding analysing detail environmental impacts that would vary depending on the electric loads covered by different power systems, the Type 10 concept was divided into Type 10-1 (fuel cell covers propulsion load and Battery covers hotel load), Type 10-2 (50-50% shared by fuel cells and batteries) and Type 10-3 (fuel cells are for only hotel load, while batteries cover propulsion load).

The power system is composed of the ammonia reforming system, fuel cells, DC/DC converters, batteries with AMP, AC/DC converters and AC propulsion motors.

7.5. Task 3: Lifecycle environmental impact evaluation

In this task, environmental impact, in particular global warming potential (GWP) which is the most severe environmental issue in the world, was evaluated through LCA. It is the process to determine the holistic prospect and benefits of using zero-carbon fuels in the UK environment under the scenarios in Tasks 1 and 2 from raw material acquisition through production and use to the end-of-life treatment, recycling and final disposal. Especially, an enhanced and novel method of Live-LCA introduced in section 5.2 was applied to perform more reliable, accurate and circumstantial LCA. An example diagram is given in Figure 7-5.

7.5.1. Data collection for environmental analysis

As with Task 1 and 2, relevant environmental data from a variety of sources, including historical papers, literature, and public data were collected. In addition, the existing data and recent research work were incorporated into this Task.

The collected ships' power consumption data (Table 7-2) was based on the actual operation scenario of CMAL, and organised and stored in the data library which was then connected for the analysis as key inputs.

In terms of energy consumption, the specific fuel consumption of the diesel generator using MGO was set at 205 g/kWh based on the model Volvo Penta D13-MG, and the MGO density was set at 0.855 (Nabi and Hustad, 2010). Specific fuel consumption was set considering an appropriate generator model based on 85% of the ship's output, which was determined based on the actual operating profile provided by the shipowner. The amount of hydrogen fuel used was calculated based on the following equation (Dicks and Rand, 2018).

$$H_{2\,usage} = \frac{P_e}{2V_c F} = 1.05 \times 10^{-8} \times \frac{P_e}{V_c}\ kg/s \tag{5}$$

Where, P_e is electric power of the fuel cell stack, V_c is average voltage of one cell in the stack (approximate 0.72 V), and F is Faraday constant (the charge on one mole of electrons, 96485 coulombs).

In addition, the amount of ammonia fuel used was calculated by applying the formula for hydrogen consumption, considering the hydrogen gravimetric density of ammonia, 17.8% wt (Makhloufi et al., 2019), and assuming that ammonia fuel covers the energy consumed during ammonia cracking (1.41 kWh/kg NH_3) (Brown, 2017).

Based on the upper-mentioned information, the following fuel consumption factors are summarised: MGO for 0.1753 kg/kWh; Hydrogen for 0.0525 kg/kWh; Ammonia for 0.4176 kg/kWh.

Table 7-4 was made up based on data from GaBi software, Department for Business (2022), Jeong et al. (2020), Hydrogen Council (2021), and Boero et al. (2021).

Table 7-4. Functional unit of GWP (kg CO_2 eq. / kWh) for energy sources

MGO (kg CO_2eq. / kg)	Electricity (kg CO_2eq. / kWh)		Hydrogen (kg CO_2eq. / H_2 kg)		Ammonia (kg CO_2eq. / NH_3 kg)	
3.64241	Coal	0.912	Blue	3.9	Blue	1.12
-	Oil	0.706	Green	0.5	Green	0.24
-	Natural gas (LNG)	0.565	-	-	-	-
-	Nuclear	0.00568	-	-	-	-
-	Hydro	0.00624	-	-	-	-
-	Wind	0.0105	-	-	-	-

-	UK electricity	0.23112	-	-	-	-
-	Solar	0.0671	-	-	-	-

The transportation part, which is omitted in most LCA studies, is essential to consider for fuels that require cooling during transportation, such as hydrogen and ammonia. Therefore, to perform an environmental impact assessment on the energy used when those are transported, Table 7-5 was summarised based on reports (Department for Business, 2022, Iulianelli and Basile, 2020, Brown, 2017, Lloyd's Register, 2020, Allen, 2018).

Table 7-5. Emissions by means of transport and energy used during transport

MGO (Truck) **(kg CO_2 eq. / km)**			**Hydrogen** **(kWh / H_2 kg)**		**Ammonia** **(kWh / NH_3 kg)**	
Load	50 %	Full				
< 3.5 tonnes	-	0.24	Liquefaction	11.11	Cracking	1.41
3.5 - 7.5 tonnes	0.48	0.52	Storage	1.97	Liquefaction & storage	0.04
7.5 - 17 tonnes	0.61	0.69	Road transfer	0.39	Road transfer	0.14
> 17 tonnes	0.93	1.10	(kWh / kg, per 100 km)		(kWh / kg, per 100 km)	

The research purpose is to understand the difference in environmental impact when applying conventional fuel (MGO) and zero-carbon fuels to electric propulsion ships and to provide insight into alternative fuel introduction from the perspective of environmental impact. Therefore, the installed equipment of the ship was excluded from the scope of the study and the research results were analysed/organised through comparative analysis.

7.5.2. Development of LCA model

The Live-LCA method was developed to aid and enhance the knowledge obtained from past research works. The proposed method was directly applied for environmental analysis (Task 3.3 which is section 7.5.3).

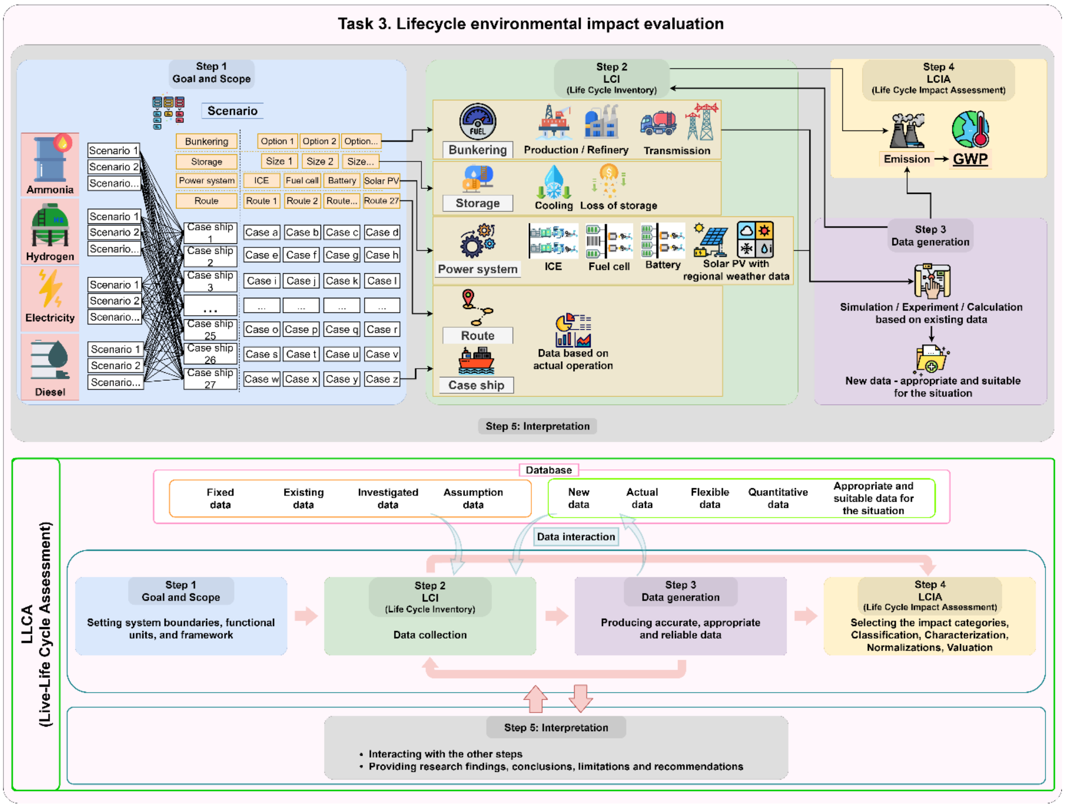


Figure 7-5. The process of the Lifecycle environmental impact evaluation through Live-LCA

Data generation technique was applied to Types 4, 7 and 10 where the solar PV systems were proposed for each ship, and then Live-Lifecycle Assessment (LLCA) which was the proposed LCA method was performed.

The number of solar panels installed was determined based on the assumption of installing solar panels on 80% of the ferry deck area. The power generated by solar panels was obtained by simulation using MATLAB/Simulink rather than assumptions based on the capacity of the panels. The input value of the simulation was monthly average weather data, which can be checked on RETScreen, on the sailing route based on the ship operating plan. In addition, the Maximum Power Point Tracking (MPPT) method was applied during the solar PV system simulation. In this study, the chosen model of solar panel was SunPower SPR-X21-345 that maximum power is 345 W. Through this, the monthly amount of electricity produced by the Solar PV system for each case ship was calculated, and by summing them, the annual amount of it for the case ships was summarised as shown in Table 7-6 below.

Table 7-6. Summary of simulation results for all case ships

No	**Ship**	**Power Generated by Solar PV system (kWh/year)**	**No**	**Ship**	**Power Generated by Solar PV system (kWh/year)**
1	MV Isle of Cumbrae	54,414	15	MV Loch Tarbert	44,905
2	MV Argyle	183,946	16	MV Loch Buie	53,030
3	MV Bute	183,946	17	MV Loch Striven	44,905
4	MV Loch Dunvegan	119,211	18	MV Clansman	276,721
5	MV Loch Shira	126,025	19	MV Isle of Lewis	331,329
6	MV Caledonian Isles	252,150	20	MV Loch Fyne	104,593
7	MV Isle of Arran	230,160	21	MV Lord of the Isles	235,874
8	MV Catriona	90,322	22	MV Hallaig	90,175
9	MV Loch Ranza	51,018	23	MV Loch Alainn	91,796
10	MV Hebridean Isles	228,418	24	MV Hebrides	265,588
11	MV Finlaggan	248,882	25	MV Loch Portain	119,140
12	MV Clansman	234,585	26	MV Loch Seaforth	352,330
13	MV Coruisk	136,818	27	MV Loch Nevis	97,515
14	MV Lochinvar	79,677	-	-	-

7.5.3. Comparative environmental analysis

Comparative LCA has been conducted across 18,981 credible scenarios (see Figure 7-6) to determine the holistic prospect and benefits of using zero-carbon fuels in the UK environment under the scenarios in Tasks 1 and 2 from raw material/energy acquisition to end-of-life treatment.

The proposed LCA method in Section 5.2 and 7.5.2 allows obtaining general observations on the environmental impact of case ships, as well as general insights into other vessels.

The global warming potential (GWP) was considered as the reference environmental impact to derive the best scenario among all credible ones. In other words, GWPs were estimated throughout the production, transportation, storage, and use of fuels to suggest the most feasible propulsion types and fuels for each case ship.

(a) Comparative environmental analysis in terms of fuel production and use

First, GWPs from the energy production and onboard use stage for each ship and each design type were compared. The fuel types considered in the analysis were marine gas oil, electricity produced from coal, oil, natural gas, nuclear, hydro, and wind, electricity from the UK national grid, solar PV system, blue and green hydrogen, and blue and green ammonia. Given this, a total of 208 scenarios per ship were reviewed.

It was confirmed that Type 3 with the electricity from nuclear would have the least GWP across all scenarios. Next, Type 3 with electricity generated from hydro was placed on the second-lowest GWP, and Type 6-3 with green hydrogen and electricity from nuclear was followed as the third-lowest GWP. Conversely, if relying on the electricity from coal, the same Type 3 would turn to produce the greatest levels of GWP for all 27 ships commonly. Similar trends were observed with most types if their electricity production relies on coal. For example, in case that Type 4, and Type 2-3 are subject to coal-based power generation, the GWP levels become significantly high compared to the same types with different power resources.

Based on the UK production method, when only the production and use of fuel are considered, Type 5 with green hydrogen generates the least GWP, and shows only 3.5% of it compared to Type 1. It was followed by Type 7-1 and Type 6-1 using green hydrogen as fuel, and only 4.5% and 5.0% of GWP were generated compared to Type 1, respectively.

Table C-1 presents the summary of the GWP functional units for the 27 case ships from the perspective of only fuel production and use. It apparently highlights the importance of lifecycle assessment to obtain a proper understanding of how to contribute to cleaner shipping in the Scotland shipping sector. It is clear that a simple fuel replacement from diesel to electricity, hydrogen or ammonia does not always guarantee the best outcomes. For instance, the primary source of electricity generation is highly important, as can be seen from the following comparison of GWP of 5.680×10^{-3} kg CO_2 eq. per kWh when using electricity from nuclear and GWP of 9.120×10^{-1} kg CO_2 eq. per kWh if the electric energy is produced by coal. That is, depending on how and what resources are used to generate electricity, it produces the least GWP or causes the most GWP. When using electricity made from coal, 22.1% more GWP was emitted than when using MGO, a conventional fossil fuel. Similarly, even when hydrogen and ammonia are used as marine fuels, the environmental impacts on the ship's lifecycle would vary depending on the energy production methods. That is, it can be intuitively confirmed that the environmental benefits are large only when, where, and how green hydrogen and green ammonia are used as marine fuels. In this regard, this study finding highlights the importance of understanding the current energy infrastructure and availability in the working area, in order to achieve the best solutions.

(b) Comparative environmental analysis in terms of fuel lifecycle

In addition to the fuel production and onboard usage as discussed above in Section 7.5.3 (a), this section deals with the full LCA by adding fuel transport and storage phases in the analysis. A total of 208 scenarios depending on the fuel production and use were identified and defined. The environmental impacts associated with differences in fuel production location (1 for MGO 1, 13 Hydrogen 13, Ammonia 2) and fuel transport means were further included in the analysis. 703 scenarios per vessel and a total of 18,981 scenarios for the whole ships were investigated in overall consideration of the lifecycle emissions from the fuels used for fuel transport from the production site to each vessel, fuel storage, and the transport intervals and distances. The GWP values through the various scenarios were calculated following the flow of the process shown in Figure 7-6, and summarised by each type and expressed in Table C-2. When the GWPs were calculated from the perspective lifecycle including fuel storage and transport, a fuel production site was selected that is the nearest one from the sailing route of each case ship.

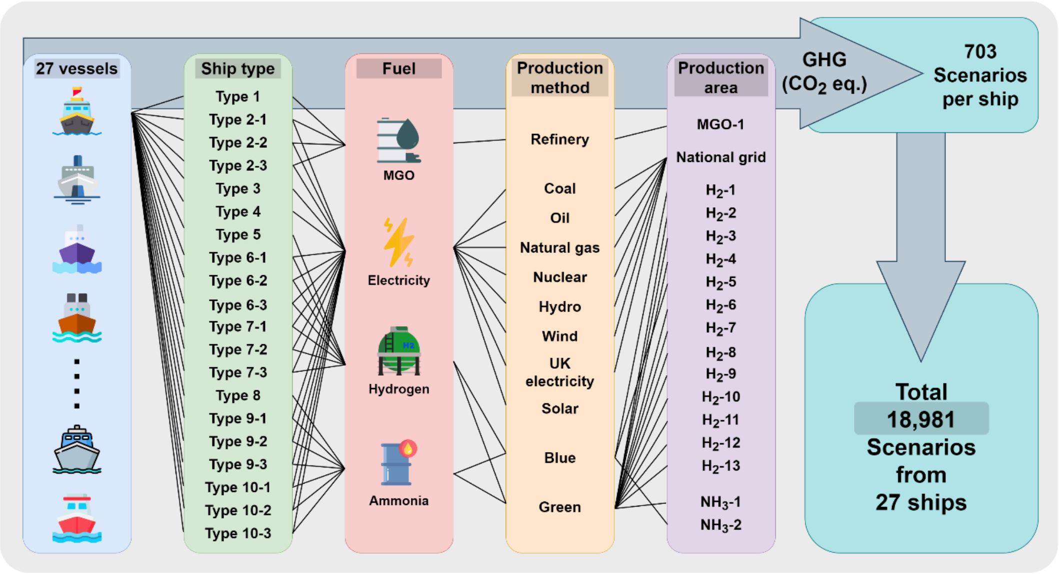


Figure 7-6. GHG emission calculation flaw

As shown in Table C-2 and Figure 7-7, Type 5, 6-1, and 7-1 fuelled by green hydrogen in all sample ferries operating in Scotland were identified as the best ship design options in terms of minimising lifecycle GWPs when the transportation and storage of fuel are included. Even though hydrogen transported in a cryogenic state consumes energy at a significant level during transport and storage, ammonia fuel has a worse environmental impact. This is because its hydrogen gravimetric density is 17.8% wt. Therefore, a larger amount of production, transport and fuel consumption is required. Moreover, significant energy is consumed during ammonia cracking to separate hydrogen from ammonia (1.41 kWh/kg NH_3) (Brown, 2017). Therefore, considering this as a whole, it was confirmed that less GHG was generated when hydrogen was used as fuel from a lifecycle point of view. For this reason, as can be plainly seen from the comparison between Table C-1 and Table C-2, even if the transport part is included, the use of ammonia as a fuel for electric propulsion ships and the accompanying Types 8, 9, and 10 could not be suggested as the ideal ship design in terms of GWP.

However, since liquid ammonia has a density of 681.9 kg/m^3 while the density of liquid hydrogen is 70.85 kg/m^3 (Siddiq et al., 2011, Wang et al., 2022), consideration of storage space is a necessary factor and inescapable.

On the other hand, if Type 3 is applied with 100% nuclear electricity, the functional unit of this option would be as low as 5.680×10^{-3} kg GWP per kWh, showing the lowest figure. Type 3 with 100% hydropower usage and Type 4 with solar + nuclear are followed by 6.240×10^{-3} and 7.366×10^{-3} kg CO_2 eq./kWh respectively. Although the emission generated during transport to the vessel differs depending on the fuel production area, the GWP functional unit can be summarised as shown in the following table based on the total sample vessel by applying the average value.

Based on Table C-2, a graph of functional units under the current UK scenarios where the electricity would be supplied from the UK national grid to ships and all fuels are supplied from the UK production sites is expressed in Figure 7-7 below. The UK scenarios were then compared to the best and the worst scenarios which mark the lowest/the greatest functional units. This comparison would suggest some adequate directions for future UK energy policy and the energy pathway with confidence.

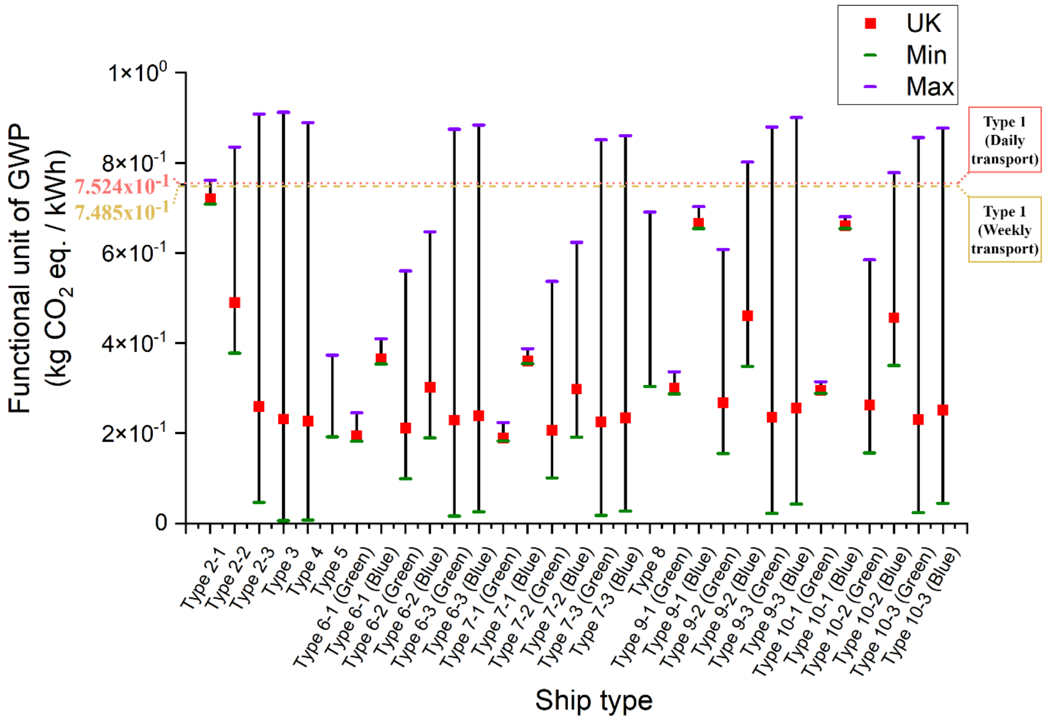


Figure 7-7. Functional unit of GWP based on 27 ferries operating in Scotland on average

As can be seen in Figure 7-7, all proposed types were revealed capable of reducing lifecycle emissions significantly, compared to using the conventional MGO, as long as the case ships are subject to the current UK energy production infrastructure and supply chain.

Table 7-7. Lifecycle Global Warming impact of the vessel operated in Scotland

Type	Type of the electric propulsion ship	GWP ratio		Fuel
		Blue	Green	
1	Diesel generator (ICE- Internal Combustion Engine)	100%		Diesel (MGO)
2-1	Hybrid ship (Diesel generator (main) + Battery (sub))	96.3%		Diesel (MGO) + Electricity
2-2	Hybrid ship (Diesel generator (50%) + Battery (50%))	65.5%		
2-3	Hybrid ship (Diesel generator (sub) + Battery (main))	34.7%		
3	Full battery ship	30.9%		Electricity
4	Battery + Solar PV system	30.3%		Electricity
5	Hydrogen fuel cell	49.9%	26.0%	Hydrogen

6-1	Hydrogen fuel cell (main) + Battery (sub)	48.9%	26.3%	Hydrogen + Electricity
6-2	Hydrogen fuel cell (50%) + Battery (50%)	40.4%	28.4%	
6-3	Hydrogen fuel cell (sub) + Battery (main)	31.9%	30.6%	
7-1	Type 6-1 + Solar PV system	48.2%	25.7%	Hydrogen + Electricity
7-2	Type 6-2 + Solar PV system	39.8%	27.8%	
7-3	Type 6-3 + Solar PV system	31.3%	30.0%	
8	Ammonia fuelled hydrogen fuel cell	92.3%	40.5%	Ammonia
9-1	Ammonia fuelled hydrogen fuel cell (main) + Battery (sub)	89.0%	40.0%	Ammonia + Electricity
9-2	Ammonia fuelled hydrogen fuel cell (50%) + Battery (50%)	61.6%	35.7%	
9-3	Ammonia fuelled hydrogen fuel cell (sub) + Battery (main)	34.2%	31.4%	
10-1	Type 9-1 + Solar PV system	88.2%	39.4%	Ammonia + Electricity
10-2	Type 9-2 + Solar PV system	61.0%	35.1%	
10-3	Type 9-3 + Solar PV system	33.6%	30.8%	

Note: Red ≥ 70%; 70% > Orange ≥ 40%; 40% > Blue ≥ 30%; 30 > Green

Table 7-7 represents the numerical UK basis summary of Figure 7-7 which reveals that the effect on global warming could differ by 2-10 or more times depending on the fuel production method. In particular, it was observed that there would be distinctive deviations in the lifecycle emission levels between blue and green fuels associated with Type 5, Type 8, Type 9-1, and Type 10-1.

As mentioned in Section 7.5.3 (a) above, when fuel transport and storage of fuel were not considered, it was confirmed that the smallest GHG emissions appeared in the order of Type 5, Type 7-1, and Type 6-1 if green hydrogen is used as a fuel. Importantly, even if the transportation and storage of fuel are taken into account, this trend does not change significantly. When the new fuel was applied to ships operating in Scotland and reviewed from the perspective of the lifecycle considering fuel production, transport, storage, and use, it was also confirmed that the lowest GHG emissions occurred in the order of Type 7-1, Type 5, and Type 6-1. When using green hydrogen as a fuel, these types showed GWP of 25.7%, 26.0%, and 26.3%, respectively, compared to Type 1 using fossil fuels.

It has been studied that Type 3 and Type 4 that use electric energy as fuel generated about 30% of GHG emissions and Type 8, 9, and 10 that use ammonia as fuel occurred approximately 30-40% of GWP, compared to Type 1.

In other words, for the case ships under the current service plans, Type 7-1 with hydrogen fuel cell plus battery and solar PV system as auxiliary energy sources or Type 5 with hydrogen fuel cell options were identified as the best solutions to minimise the lifecycle emissions from the shipping activities in Scotland.

The analysis results further highlight the significance of using LCA to determine the best environmental solutions. The current environmental indicators, such as EEDI, EEOI and EEXI are only relevant to calculating the CO_2 emissions on board. Paradoxically, from those indicators' point of view, all Type 3 to Type 10 is defined as "zero-emission" options as electricity, hydrogen, and ammonia all emit no CO_2 on board when they are used as marine fuels. LCA can remedy the shortcomings of the current IMO indicators.

From the lifecycle point of view, the analysis results are far from zero emissions. It reveals that emission levels, as well as functional units for all Types, are highly subject to the production method of the fuel. In some cases, as shown in Type 2, Type 3, Type 4, Type 6-3, Type 7-3, Type 9-3, and Type 10-3 in Figure 7-7, it has been found that electric energy, hydrogen, and ammonia produce even more emissions than MGO.

7.6. Task 4: Development of roadmap for UK shipping

As an extension of Task 3 (Section 7.5), this task was proposed to offer some meaningful insight into for UK's successful zero-carbon shipping by offering scale-up information to obtain the roadmap for the future UK zero-carbon business. It was conducted with the same LCA method, and the analysis scope proposed in Sections 3.3.2 and 3.3.3 but applied to 5,656 large-scale ships under the UK flagship (see Figure 7-8). Changes in GHG emissions were identified for the case where all of these vessels are converted to electric propulsion ships and the carbon-free fuel considered in the previous Tasks is applied, and finally how much Global Warming Potential could be reduced is presented.

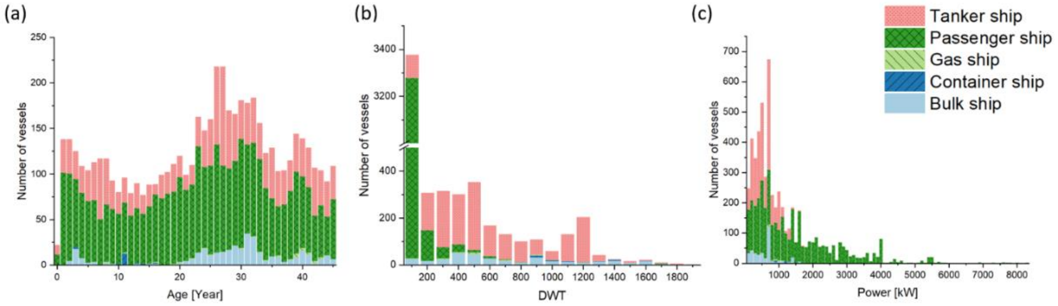


Figure 7-8. Distribution chart of the number of world fleets (5,656 ships) database according to power (kW), deadweight (DWT), age (Year)

Figure 7-8 shows that 5,656 vessels in the database range from 0 to 45 years and are distributed in different age groups. These vessels typically have engine powers ranging under 2,000 kW, with vessels under 100 DWT accounting for more than 50%.

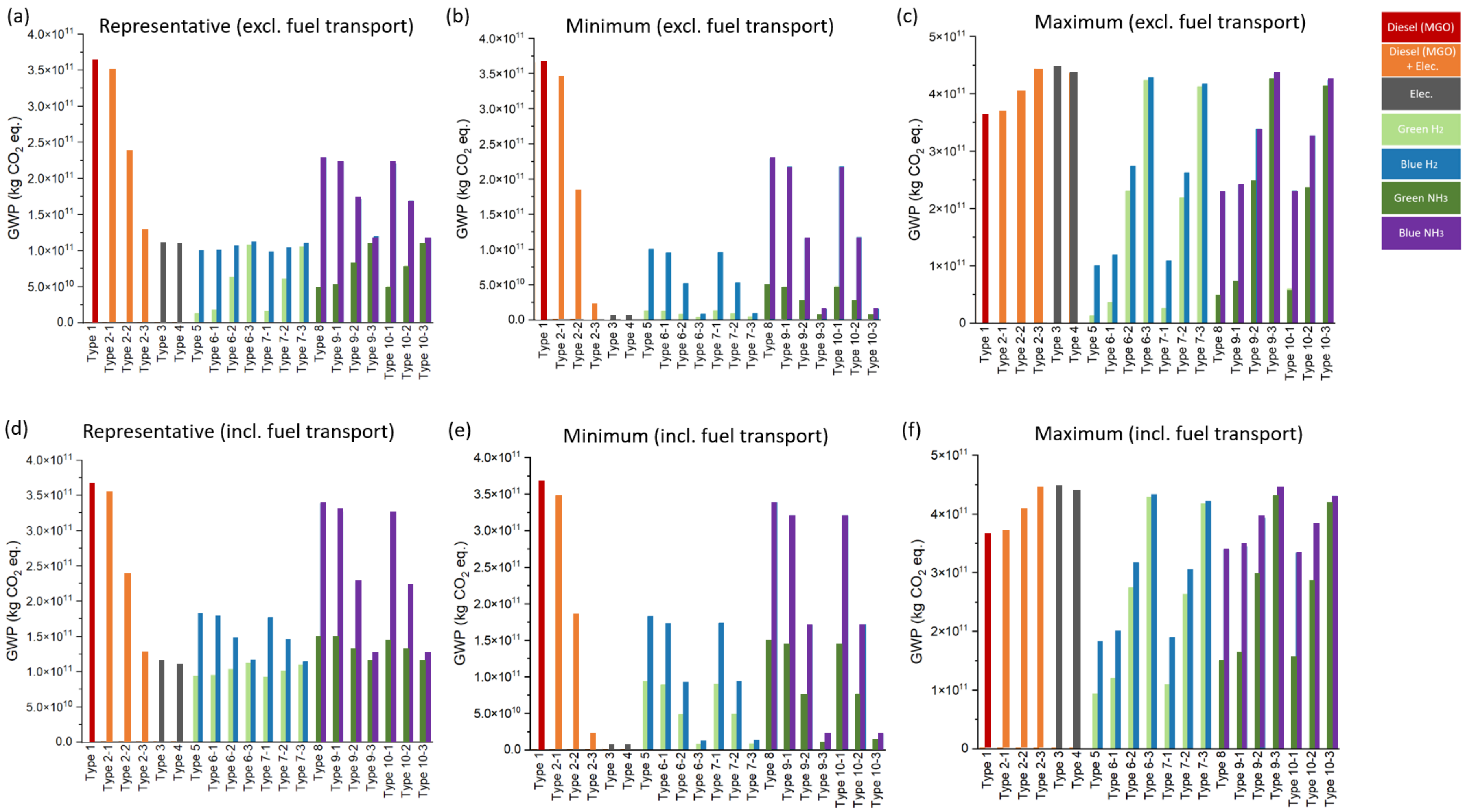


Figure 7-9. Comparison of environmental impacts of the UK registered fleets (5,656 ships) according to different fuel sources

Figure 7-9 compares the environmental impact according to the maximum, minimum, and representative (current UK energy infrastructure) values for the 5,656 ships. Figure 7-9 (a), (b) and (c) represent cases where the fuel transport phase is not included, while Figure 7-9 (d), (e) and (f) do. The environmental gaps obtained from each type between those figures show the high impact of the transport phase on the results.

As it can be obviously seen that electricity is the most suitable fuel source for reducing the GWPs of ships from Figure 7-9 (b) and (e), but depending on how it is produced, it can have the opposite effect (see Figure 7-9 (c) and (f)). Also, through the GWP graphs in the case of changing all UK registered ships to electric propulsion ships, it was evidently confirmed that green hydrogen and green ammonia are much more suitable alternatives to lower GWP than blue hydrogen and blue ammonia.

As a result, when applying carbon-free fuels to vessels to reduce GHG based on operating in Scotland, a total of 2.715×10^{11} CO_2 eq. can be diminished during their life span (25 years) if all ships registered in the UK are changed from type 1 using MGO to type 7-1 using green hydrogen as fuel and installed battery with the solar PV system.

Also, as shown in Figure 7-9, Type 5, Type 6-1, Type 7-1, Type 8, Type 9-1 and Type 10-1 tended to increase GWP to the highest when the fuel transport phase is considered. That means, it can be argued with certainty that in the case of carbon-free fuel, a significant amount of energy is consumed during transportation, and therefore, the environmental impact of the transportation sector must be taken into account.

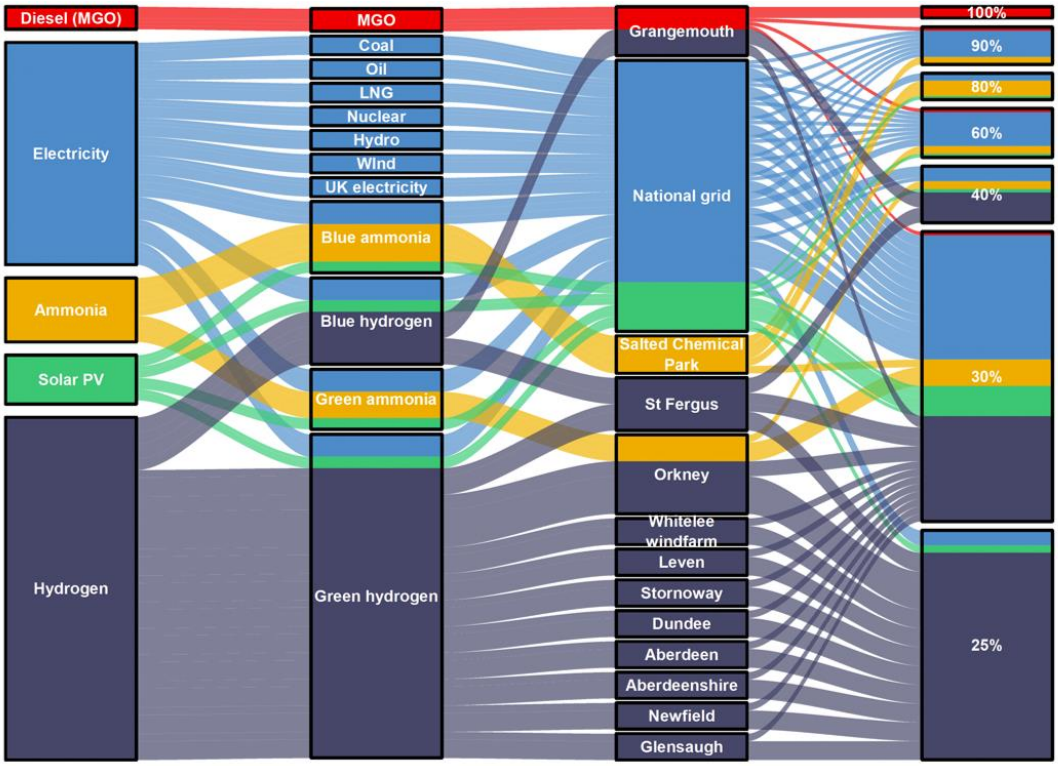


Figure 7-10. Lifecycle footprint for UK marine fuels expressed as emission ratio relative to diesel fuel

Figure 7-10 is a flow diagram showing the emission ratio that occurs when diesel (MGO), electricity, solar PV, hydrogen and ammonia which are fuel sources applied in this study to ships, are produced in various ways and supplied to ships. Each fuel source has different emission values depending on the energy production method and production area, and it is revealed which fuel can reduce GWP in the UK through various possible scenarios. Overall, the emission ratio showed a tendency to be lower when green hydrogen, solar PV and green ammonia were used rather than other fuels. Ultimately, this flow diagram can present a roadmap to the UK shipping industry.

7.7. Chapter summary and conclusions

So far, there have been various studies on shipping fuels. However, as identified in section 3.2.3, although many studies have been conducted, precise environmental impacts of fuel use have not been presented for the shipping sector. A significant number of studies have presented environmental indicators that can be improved in fuel conversion in the downstream aspect considering only the user stage. In addition, some other studies have conducted studies involving upstream stages to consider the production side of fuel, but they have simply grasped the environmental impact occurring at the production stage.

To understand the environmental impact of fuel used in ships from a holistic perspective, it is crucial to comprehensively consider steps such as transportation and storage in addition to the aspects of production and use. This case study was conducted to overcome these limitations identified in previous studies. The scope of the research is to compare various zero-carbon fuels, such as hydrogen, ammonia and electricity, with conventional fossil fuels, MGO, to identify and provide environmental benefits. In this process, not only the downstream of the fuel but also the upstream were considered, and energy consumption for the transportation and storage of zero-carbon fuel, which was omitted in many studies, was also considered. In other words, it overcomes the limitations of existing studies about the environmental impact of energy parts of ships and LCA in the shipping field from a holistic point of view.

This case study proposes a roadmap to achieve low-carbon shipping through a comprehensive and in-depth study. Moreover, based on the comprehensive scope of various ship activities and clear identification of ambiguous environmental impacts, it presents a new paradigm for LCA research in the energy section of the maritime sector.

The research results intuitively show a different view of the common stereotype about carbon-free fuels from the perspective of the lifecycle. It is also clearly shown that lots of energy are consumed during transport for carbon-free fuels such as hydrogen and ammonia from this case study. Therefore, this process should be included in the analysis for reliable environmental impact assessment.

In this study, the Live-LCA methodology was employed due to the absence of available information on the quantity of energy that can be generated from solar panels when installed on selected ferries. For this purpose, the ship system was modelled using MATLAB/Simulink, and the amount of power generated by the solar PV system was determined via simulation based on the environmental data pertaining to the actual sailing route of the ferries.

As a result of analysing the global warming potential by considering Scotland's energy industry and infrastructure and applying the Live-LCA methodology, when electric propulsion ships operate in Scotland, the lowest GHG emissions (25.7% compared to using MGO) occur when hydrogen-fuelled fuel cells cover the main load and batteries charged by inland power with the solar PV system are responsible for the other loads.

Although hydrogen transport consumes more energy than ammonia, in this study, when hydrogen is used as a fuel, the reason why it was evaluated better than ammonia fuel in terms of the lifecycle is that a lot of energy is required in the ammonia cracking process. Thus, if fuel cells that can directly use ammonia as a fuel or an ammonia fuel internal combustion engine are applied, more environmentally friendly results can be obtained than a fuel cell system that uses hydrogen as a fuel. As a result of LCA in this scenario, when ammonia is directly used as fuel and inland electricity and solar PV system are used as power system to a ship together, it showed a GWP value of 22.2% compared to the case of using MGO.

Above all, when evaluating the environmental impact in consideration of the lifecycle from a holistic point of view, it was evidently confirmed that the evaluation result was remarkably different depending on the fuel/energy production method and the energy sources used in the production.

8. REAL-TIME LIFE CYCLE ASSESSMENT (RT-LCA) FOR SHIPPING

8.1. Introduction

The other limitation of the conventional LCA methodology, as identified in Chapter 4, is that it fails to accurately reflect the characteristics of a ship operating in an ever-changing environment. The current LCA methodology is based on static states and cannot cover the continuously changing ship operating conditions such as wind speed, wave height, solar radiation, engine load, and engine speed. To address this issue, Real-Time LCA (RT-LCA) was proposed as a tool that can evaluate the environmental impact of a ship in a dynamic environment.

This chapter introduces the RT-LCA methodology and its superiority compared to the existing LCA methodology in evaluating the environmental impact of a ship in real-time using available data. This approach enables a detailed and accurate evaluation of the environmental impact, moving away from the estimation of the ship's output value and fuel consumption during a specific period or in loads. Furthermore, since the RT-LCA methodology evaluates the environmental impact of a ship under actual operating conditions that reflect various ship conditions, it makes it readily discernable which factors influence environmental impacts and cause disparate environmental outcomes in a given situation.

8.2. Outline of the adopted method for the case study

8.2.1. Step 1. Goal and Scope

The RT-LCA has a fundamentally identical goal as conventional LCAs in terms of Well-to-Wake (WtW) analysis considering all aspects from the upstream stage to the downstream one. However, the scope of the RT-LCA is more extensive than the conventional one as it pursues to evaluate the real-time holistic environmental impact of vessels in connection with cloud data transmission from vessels or database in shipping companies.

(a) Database and data transmission

In addition to ship specification and operational profiles, key real-time input data required for RT-LCA can be classified into fuel consumption rate, engine load/speed, electric power load, ship speed and so on. Information on fuels such as their properties, production locations, and supply chains is also important for real-time WtW analysis. Those data in real-time is a vital strategy for making LCA vibrant. Hence, the RT-LCA model is to be coupled with existing data management systems/platforms onboard or onshore and the real-time data transmission is implemented via cloud method.

(b) Format of RT-LCA results

Results of conventional LCAs are often presented as a form of functional units that describe emission quantifies per each unit value (e.g. /kWh) from a lifecycle perspective. RT-LCA provides its results in a further effective way. Simply to say, the iteration of estimating functional units is performed every second and the results are plotted on graphs. This new format of LCA can clearly show not only real-time functional units but also historical trends, thereby suggesting any corrective action immediately.

8.2.2. Step 2. Life cycle inventory analysis (LCI)

LCI is a technological process that quantifies the input and output to the process and seeks the balance of mass-energy within the boundaries set in Step 1 'Goal and Scope'. This includes procedures for data collection, organisation, analysis and validation.

The operation data, transmitted from the ship or data management systems onshore, is accordingly converted into the format of key input parameters for LCA simulation. Then, RT-LCA model runs the analysis iteratively as long as input data continues to be updated.

In addition, the production sites of the fuel used on the vessel are taken into account. Because even for the same MGO, the supply and demand for crude oil differ depending on the region where it is produced, and the environmental indicators of WtT according to crude oil refining and transfer after refining are all different. Therefore, when building the database, data on the upstream stage should be secured and reflected in modelling. Based on the completed modelling and real-time input data, simulation can be performed to calculate real-time emissions generated during vessel operation.

Figure 8-1 shows LabVIEW modelling for RT-LCA. The process of LCI in RT-LCA refers to two main parts: 1) Real-Time data process; 2) LCI modelling & calculation. 1st part is a step to proceed with raw data into the LCI model, and 2nd part is to quantify up-to-date emissions over the ship's lifelong activities. In this methodology, huge amounts of real-time raw data from the vessel are fed into the modelling. The simulation calculates real-time fuel consumption from a life cycle perspective.

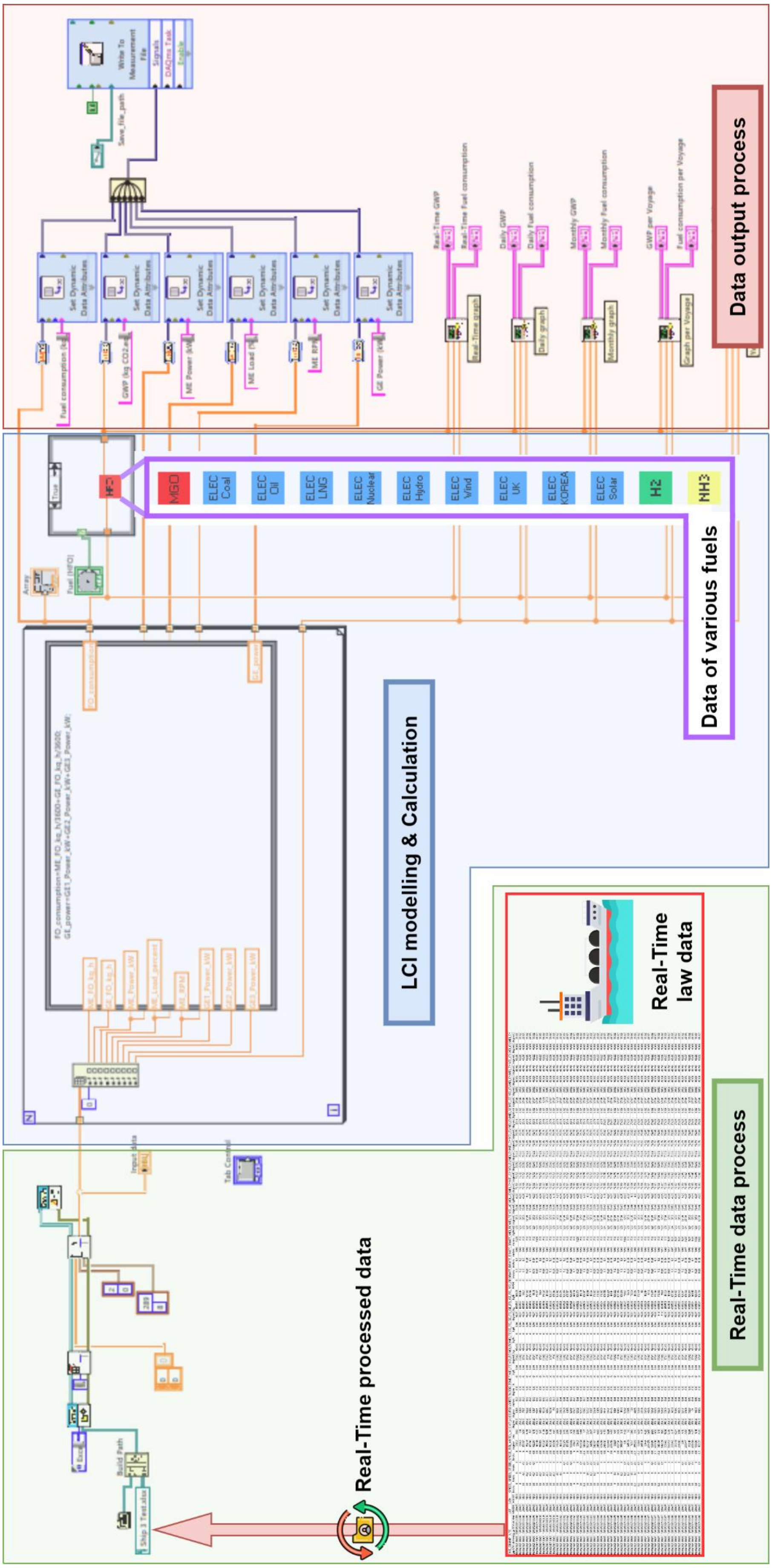


Figure 8-1. RT-LCA Modelling under LabVIEW interface (LCI and LCIA process)

8.2.3. Step 3. Life cycle impact assessment (LCIA)

LCIA is a stage in which impact indicators are presented based on the results of the LCI stage. This process involves the selection of impact categories/indicators to be presented, the classification of LCI results into selected categories, and the characterisation of the derivation of category index results.

In Figure 8-1, the LCIA process refers to the 'Data output process' where LCI results are condensed into specific impact categories: GWP, AP, EP, etc. Figure 8-2 shows some examples of how RT-LCA results (or LCIA results) can be presented. Unlike conventional LCA, instant results are presented in different time scales on a graphical interface, which can offer opportunities to obtain a general trend of environmental performances and time for corrective action needed.

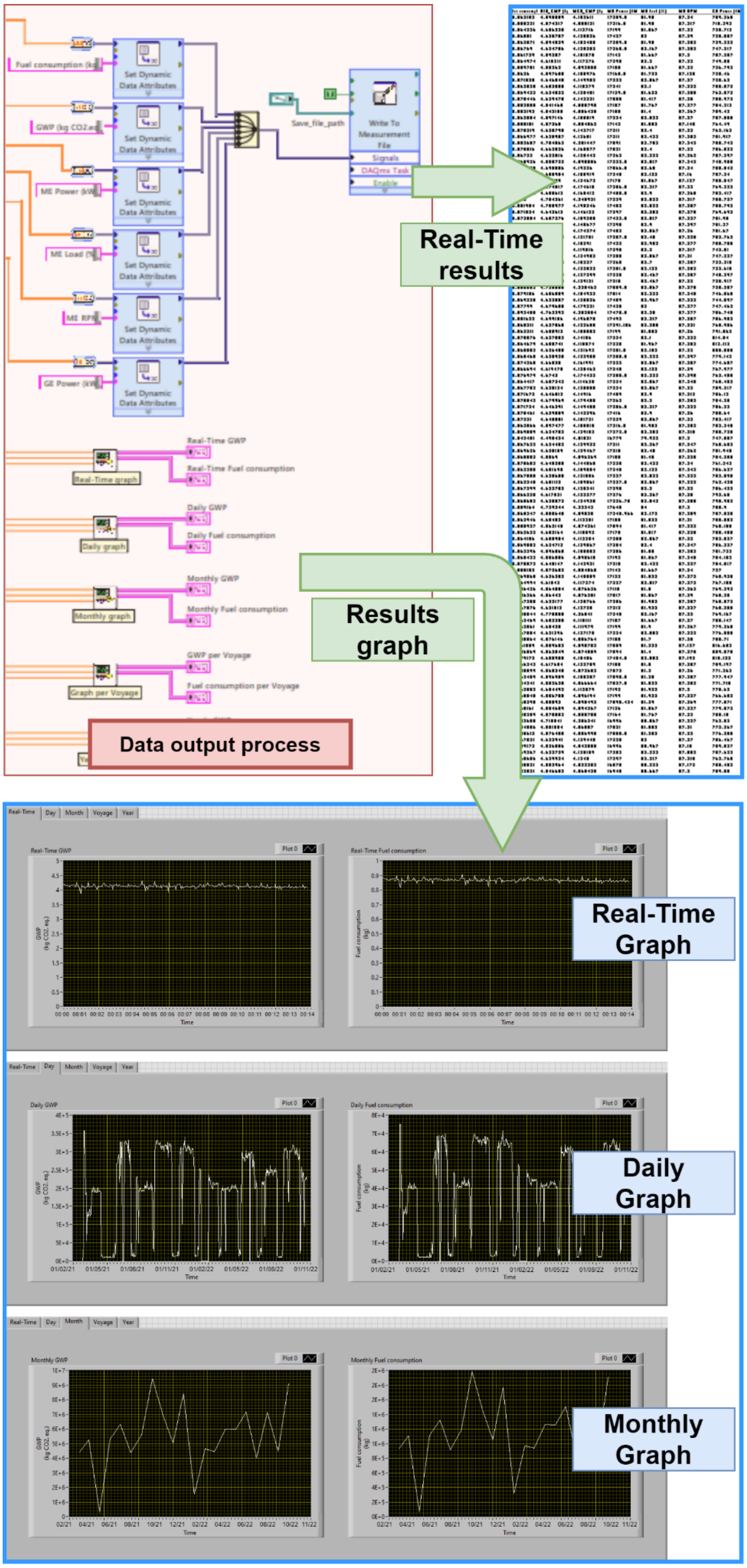


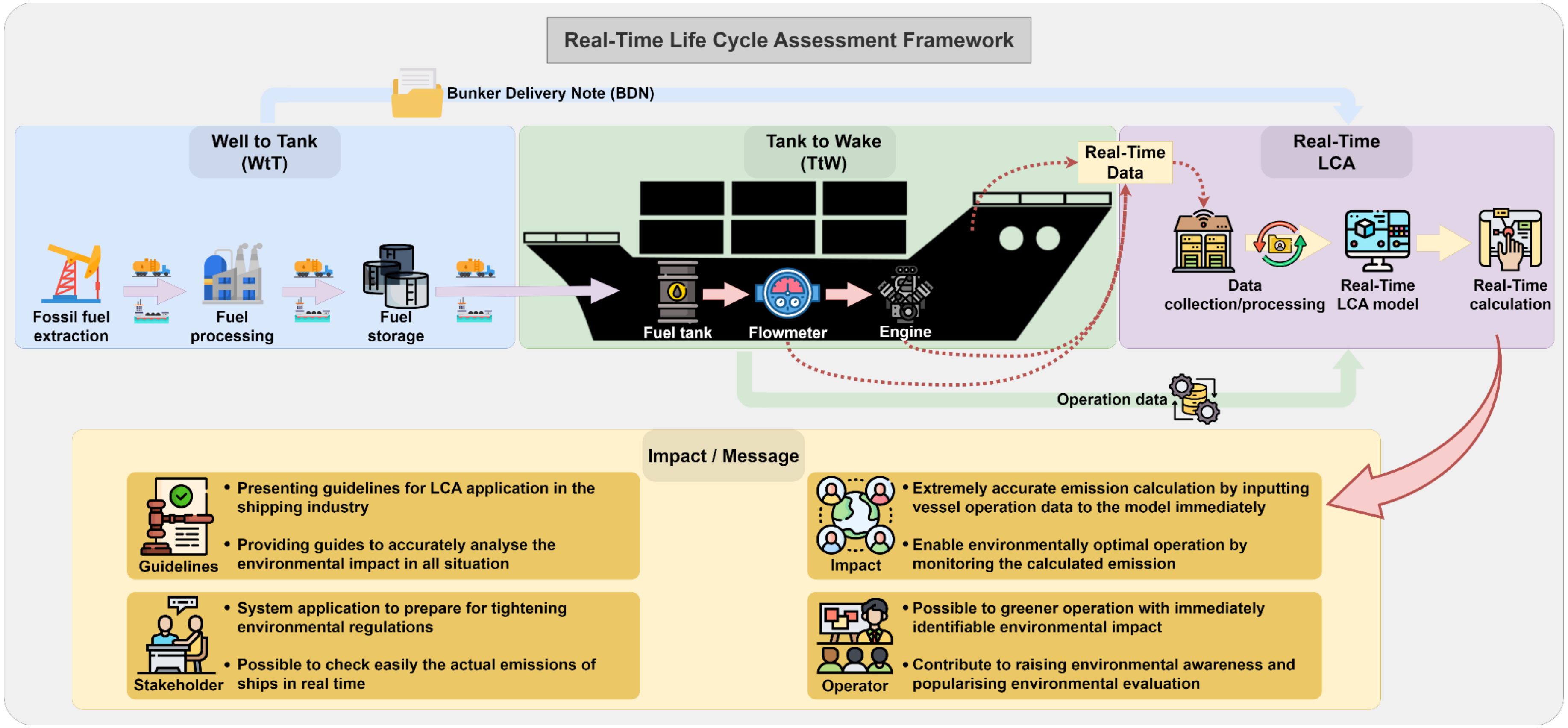
Figure 8-2. Flow and formats of RT-LCA results

8.2.4. Step 4. Interpretation

In general, Interpretation, interrelated with the other steps, is proposed for interpreting/determining key findings from LCA works. In this step, important issues are identified, the completeness and consistency of the LCA study are evaluated, and appropriate conclusions and recommendations are derived for future works.

On the other hand, this thesis particularly employs this step to highlight the benefits of RT-LCA and its potential application to the maritime industry in an effective way. Figure 8-3 outlines the key impacts of RT-LCA in the marine industry. First, the continuously updated real-time result value allows the operator working on the ship to intuitively grasp the current situation. This allows immediate action, and the updated results are instantaneously accessible. These processes can lead to real-time contributions to environmental protection. Shipping companies can also receive those results via a data transmission system so that it becomes possible to make optimal business routes and cases with immediate decision-making.

The results of RT-LCA can be classified and quantified in various ways, not only the real-time environmental impact, but also by month/voyage/quarter/year by modelling/simulation as shown in Figure 8-2. Through this, it is possible to easily set the direction of future regulatory response, and from a holistic perspective, it can greatly contribute to protecting the environment and suppressing climate change.



- Presenting guidelines for LCA application in the shipping industry
- Providing guides to accurately analyse the environmental impact in all situation

- System application to prepare for tightening environmental regulations
- Possible to check easily the actual emissions of ships in real time

- Extremely accurate emission calculation by inputting vessel operation data to the model immediately
- Enable environmentally optimal operation by monitoring the calculated emission

- Possible to greener operation with immediately identifiable environmental impact
- Contribute to raising environmental awareness and popularising environmental evaluation

Figure 8-3. Potential impacts of RT-LCA in the marine industry

8.2.5. Outline of the case study

A 172K bulk carrier currently engaged in international service was selected as a case ship. This case study can be considered as a demonstrative work presenting how RT-LCA can be applied to a marine vessel to prove its excellence. Key objectives of this study are to intuitively schematisation of real-time emissions and Carbon Footprint (CF) for the case ship from a lifecycle perspective under the RT-LCA platform coupled with real-time operation data from onboard data transmission as well as WTT data from the literature. Figure 8-4 shows an overview of the case study.

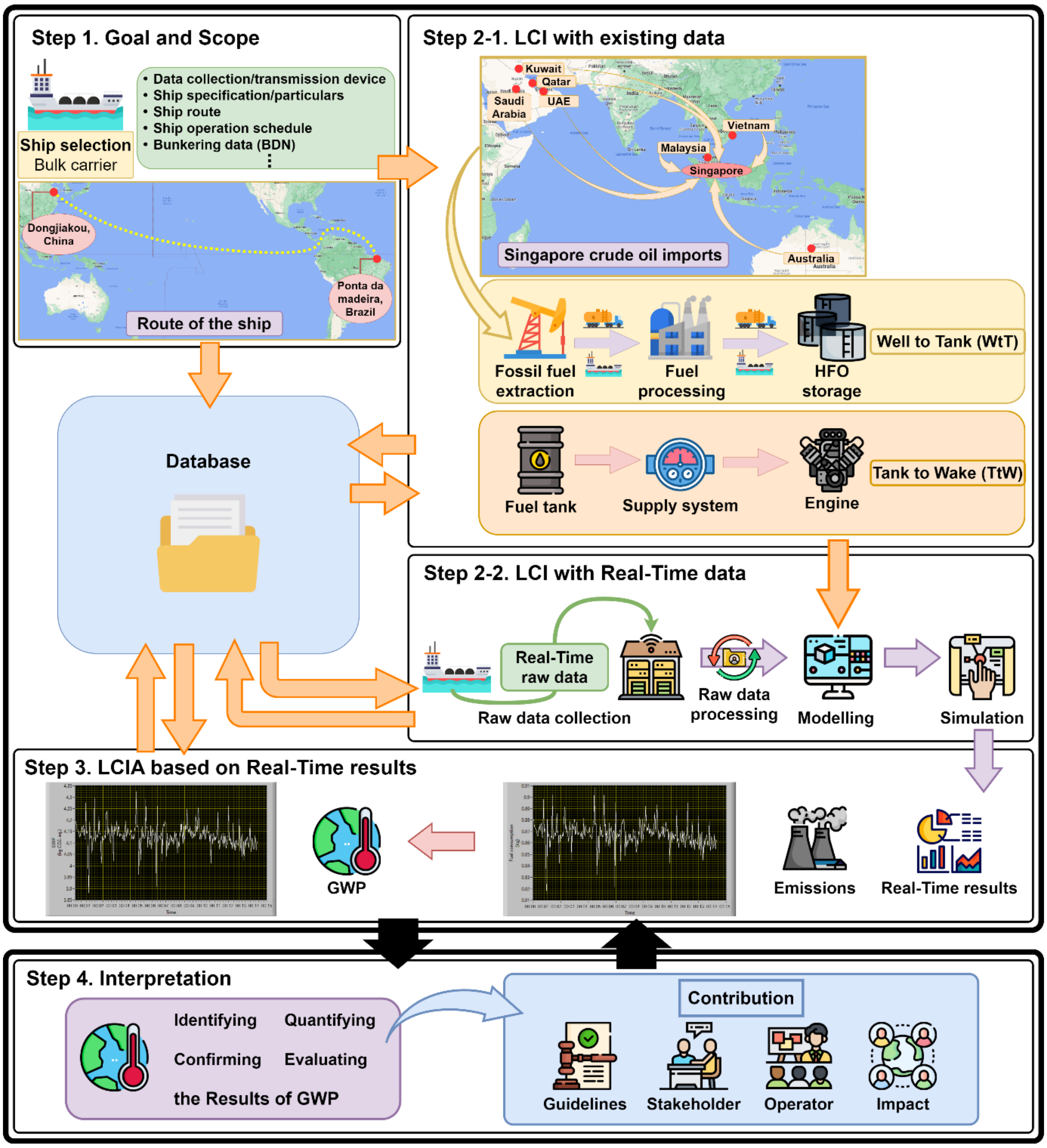


Figure 8-4. Outline of the case study

8.3. Task 1. Build-up database/transmission channel (Step 1: Goal and Scope)

In consideration of goal and scope, Task 1 is to build a database and transmission channel that inputs and outputs various types of data such as real-time operation information, basic ship specifications, operation route, operation schedules, and bunkering plans and fuel types, etc.

For the case study, the basic static data for the case ship was input to the database (referred as to existing data). In summary, it has 339.98 m in length and has one set of Main Engine with 21,000 kW × 58.9 rpm, and three generator sets of 1,570 kW. The ship has a regular voyage between Dongjiakou in China and Ponta da madeira in Brazil, and its bunkering is done in Singapore. Also, dynamic data, i.e. operating data is fed into the database continuously (referred as to real-time data). The built-up database is, then, to communicate with the Task 2 LCI analysis.

Based on this information, evaluations were performed considering all the WtW processes in terms of lifecycle. For CF calculation, factors for GWP were referred to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) (Pörtner et al., 2022); CO_2 = 1, CH_4 = 29.8, N_2O = 273 GWP.

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

The list of database essential for constructing the RT-LCA for shipping is as follows in Table 8-1.

Table 8-1. The list of database which is essential for RT-LCA in the shipping sector

Data not previously secured	Data previously secured or studied
Real-time operational data of the ship	Ship's specifications
Fuel used and fuel consumption of the ship	Country of origin with fuel imported and percentage of the imported amount by country

Real-time location of the ship	Energy consumption in fuel refining by country
Real-time weather conditions while sailing	Energy consumption in crude oil production by crude oil producing region
Bunkering port by the ship	Crude oil transfer distance
Real-time energy yield from renewable energy sources	Distance to transport refined fuel to ship
-	Energy consumption in transporting and storing fuel
-	Emissions from each fuel use

Data previously secured or studied was collected/organised through the process of 'Goal and Scope' or data collection for energy pathways. Other data which is not previously secured were collected/categorised through the data collection for the real-time LCA process.

8.4.1. Data collection for energy pathways

This is part of the basic and essential work required for this study, which includes the process of collecting, classifying, and organising vast and diverse data. It was focused on collecting data on the energy infrastructure of Singapore where a bunkering place of case ships, from literature and public data sources. As a result, as shown in Table 8-2, it was obtained upstream data related to crude oil import routes in Singapore, refining and HFO production from crude oil imported by various routes, and shipment of produced fuel, from a WtT perspective (Tan et al., 2010). Also, HFO emissions were confirmed from the TtW point of view (Ramsay et al., 2022).

Table 8-2. Well to Wake (WtW) GHG from HFO produced in Singapore

Well to Tank (WtT) GHG from HFO produced in Singapore considering crude oil imports					
Pollutants (kg/kg HFO)	Crude oil production	Ocean tanker transport	Refinery	Total	GHG (kg CO_2eq./kg HFO) (IPCC AR6)
CO_2	1.13	0.36	0.32	1.81	1.81
CO	0.000185	0.00103	0.000348	0.001563	-
N_2O	0.00129	-	0.00000558	0.001296	0.35
NO_x	0.00163	0.00963	0.00068	0.011940	-
SO_x	0.0000139	0.00696	0.00169	0.008664	-

VOC	0.000206	0.000287	0.000126	0.000619	-
PM	0.00000397	0.000229	0.0000313	0.000264	-
Tank to Wake (TtW) GHG from HFO					3.16
Total GHG from HFO produced in Singapore					5.33

8.5. Task 3. LCI with real-time data (Step 2: LCI)

This process is one of the key novelties of this study, and enables continuous real-time data reception from the selected case ship. As shown in Figure 8-5, real-time operation information such as fuel consumption during sailing, anchoring, and at berth was received in the form of raw data from the case ship bulk carrier through a platform. Received raw data went through appropriate processing and was stored in a database and storage. This data was used as modelling input for RT-LCA.

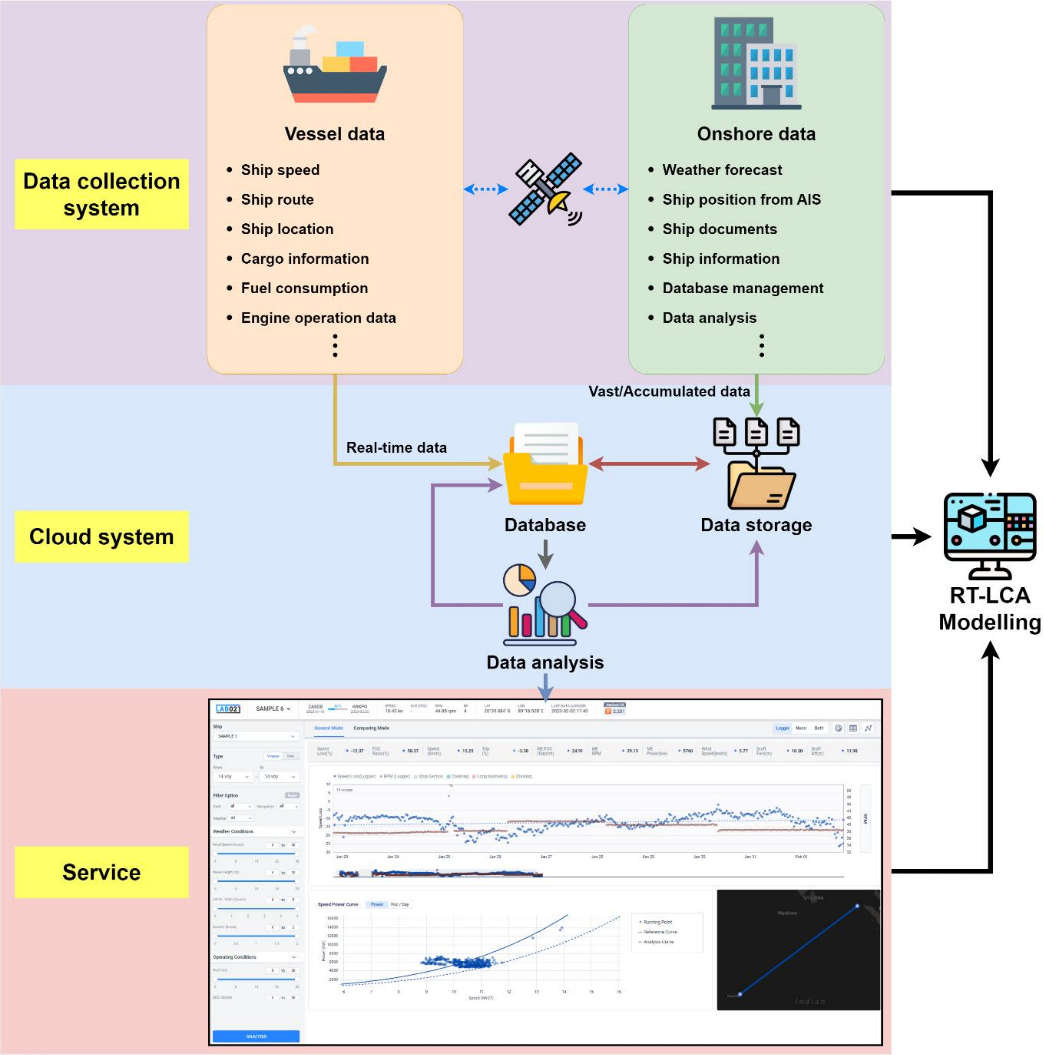


Figure 8-5. Real-time data collection process from the case ship using a platform

8.6. Task 4. LCIA modelling and simulation (Step 3: LCIA)

In order to achieve the goal set in ‘Goal and Scope’ through activities within the scope and to intuitively show the real-time GHG value, modelling was performed as shown in Figure 8-1 using LabVIEW. Based on the database obtained during data collection, a calculation formula was constructed expecting that 5.33 kg CO_2 eq. per 1 kg is generated when HFO produced in Singapore is used in a ship.

Based on this modelling, the current real-time data was received and real-time GHG result values were derived/schematised through simulation. In addition, in order to confirm the effectiveness of a more accurate methodology, RT-LCA simulation was conducted using operation data from February 2021 to the present, which has already been received and stored, and the results were compared with the results obtained by analysing the same data with the conventional LCA technique.

In this case study, GWP was evaluated in terms of lifecycle, focusing on Carbon Footprint (CF), which is currently considered the most sensitive among various environmental impacts, as set in Goal and Scope. Properly interpret data collected/derived/schematic through LCI, LCIA and modelling/simulation to contribute to various stakeholders.

8.6.1. Data analysis

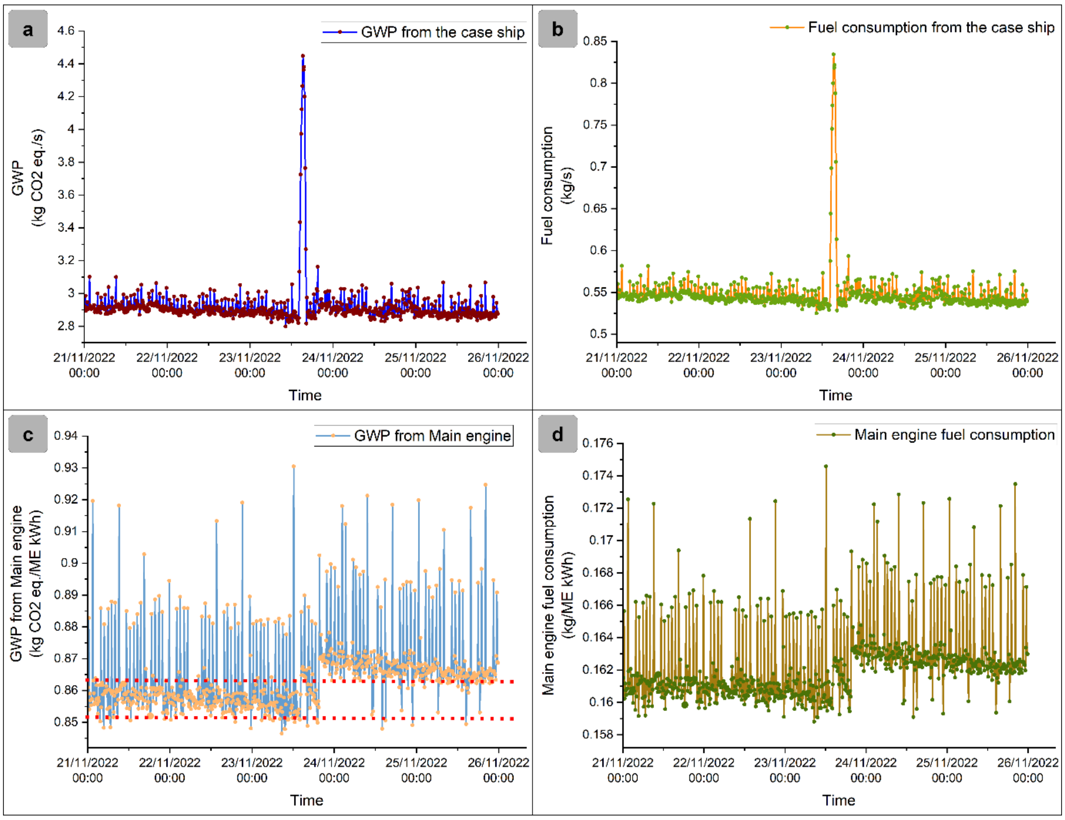


Figure 8-6. The results of Real-Time LCA

Figure 8-6 is the result of performing RT-LCA for about 5 days based on the operation data being received from the case ship. During this period, the ship generally sailed at a speed of 11.7 ~ 13.5 knots and a power of 10,700 ~ 11,200 kW and sailed at a maximum of 15.3 knots and 17,100 kW after loading up for about 2 hours. After the operation data was received through programming in real time, it was processed and used as input for modelling, and then the value of the results was saved and shown in real time as shown in Figure 8-6.

As a result, the case ship emitted 2.8 ~ 3.1 kg CO_2 eq./s in real time during the period, and up to 4.44 kg CO_2 eq./s was emitted during load up as shown in Figure 8-6 (a). When GWP compared to power was analysed for the main engine, which is the main energy consumer of the ship and shown in Figure 8-6 (c), it was confirmed that generally 0.857 ~ 0.863 kg CO_2 eq./kWh was emitted in that load, and the value rose to around 0.92 kg CO_2 eq./kWh intermittently. When only the amount of fuel consumed, emissions, and GWP were checked, it was confirmed that the GWP was high due to relatively high carbon emissions from more fuel consumption during high-load sailing for a specific period. However, when comparing the corresponding values with the power of the main engine, it was confirmed that the real-time GWP generated from the main engine during the 2-hour period of sailing with the high load was not as high as about up to 0.863 kg CO_2 eq./kWh. Therefore, based on the results of RT-LCA, a plan can be made to identify the specific cause, if cases where GWP relative to the main engine power is more than 0.863 kg CO_2 eq./kWh are not intermittent but occur continuously.

In fact, from around 20:00 on the 23rd, there were no significant changes in the fuel consumption and GWP from the entire case ship, but it was confirmed that the fuel consumption and GWP compared to the output of the main engine increased and were out of range. As a result of immediately identifying the cause at the site, the Pmax value of a specific cylinder was high, and as a result of inspection when the engine was stopped, a problem was identified in a fuel injection valve. These processes can be comprehensively accumulated to achieve more improved sailing performance in terms of the environment, and ultimately contribute to environmental improvement and progress towards an eco-friendly society that generates fewer emissions.

8.7. Task 5. Interpretation (Step 4: Interpretation)

8.7.1. Comparative environmental analysis between the conventional LCA and RT-LCA

The effectiveness of RT-LCA can be further elaborated through a comparative analysis with conventional LCA practices. Figure 8-7 presents the overviews of the two different LCAs. It clearly shows the differences in processes and formats of results.

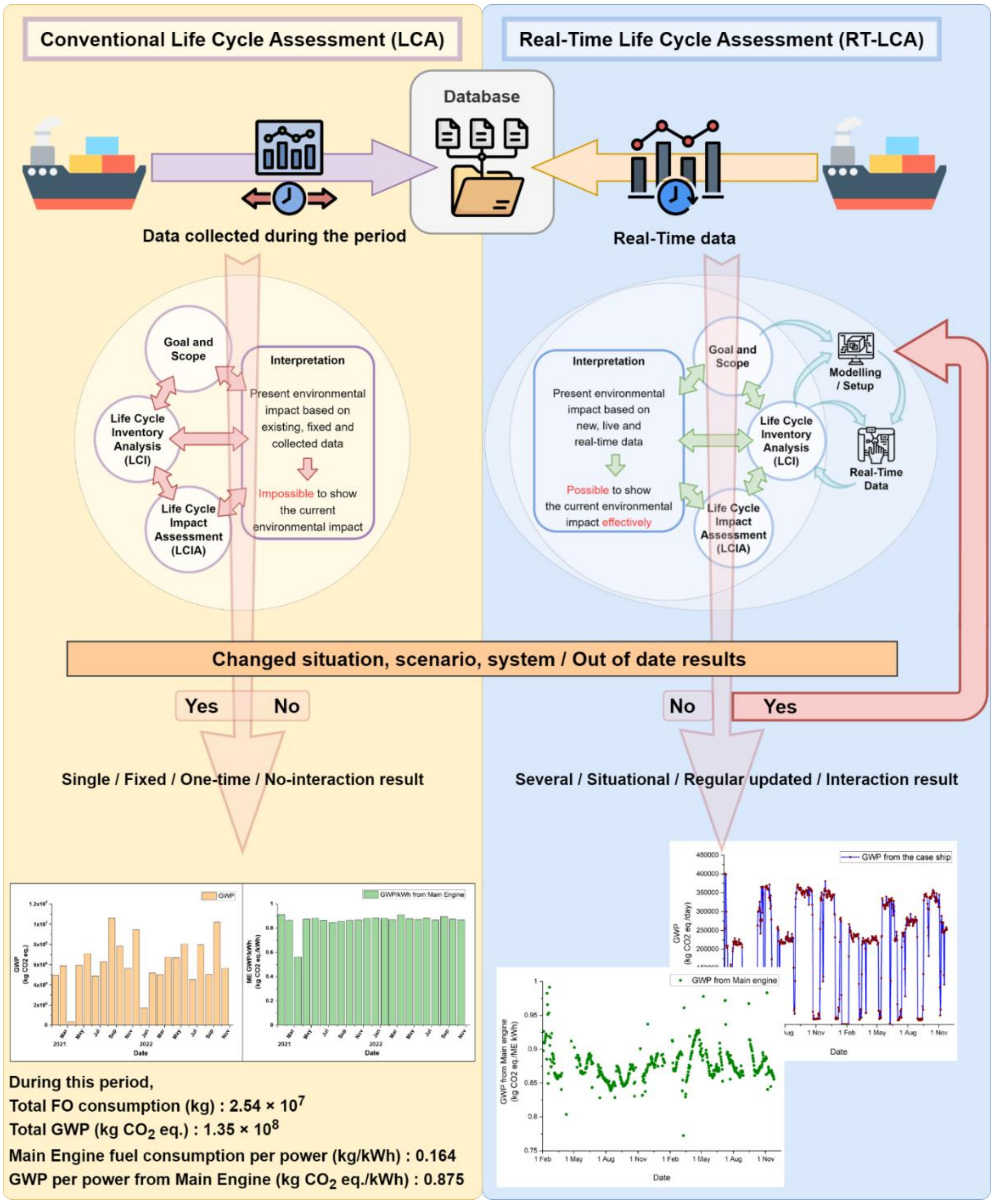


Figure 8-7. Comparative environmental analysis between the conventional LCA and RT-LCA

Another round of assessment with a conventional LCA approach was conducted in this case study. The environmental performance of the case ship was assessed based on data collected over a specific period of time from February 2021 to November 2022. The case study with conventional LCA leads to the following results: total lifecycle fuel consumption of 2.54×10^7

kg, thereby GWP of 1.35×10^8 kg CO_2 eq. and the functional unit of 0.875 kg CO_2 eq./kWh.

This comparative study points out the pitfalls of conventional LCA that attempt to use past data to predict future performance. Those simple numbers encapsulate a lot of information, but they are only valid if the ship can proceed with identical performance across the lifetime. In reality, a ship even with the same voyage route always yields different operational results by a number of factors such as voyage speeds, fuel consumptions, departure/arrival time, supply chain in bunkering, fuel properties etc. For this reason, ship operators keep records of each voyage, regularly calculating fuel consumption and emission levels in order to measure operational efficiency. In short, results from conventional LCA may provide insight into environmental impacts for the case vessels in the past, they hardly provide suggestions or corrective actions for future shipping activities.

The comparative analysis clearly shows that RT-LCA can remedy the weaknesses of conventional LCA in response to the dynamics of the case ship. Real-time data is transmitted from/to database and it is, then, fed into the LCA model for iterative simulation. Results are encapsulated and visualised on a series of graphs simultaneously. Indeed, those outputs tell us the environmental performance of the case ship at any given time with confidence. Hence, it allows immediate comparison in different time periods to monitor and confirm the efficiency of ship operation. Individual results over time can be further integrated as a general observation (or trends) of the ship performance, which will help ship operators predict future performance as shown in Figure 8-8.

In summary, the novelty of RT-LCA is to bring ‘time’ term into the static analysis, making LCA as a dynamic analysis which is much more compatible with shipping. Given that the conventional LCA relies on static analysis where time series are not taken into consideration, RT-LCA can put a big step forward in the advancement of the dynamic marine environmental impact assessment.

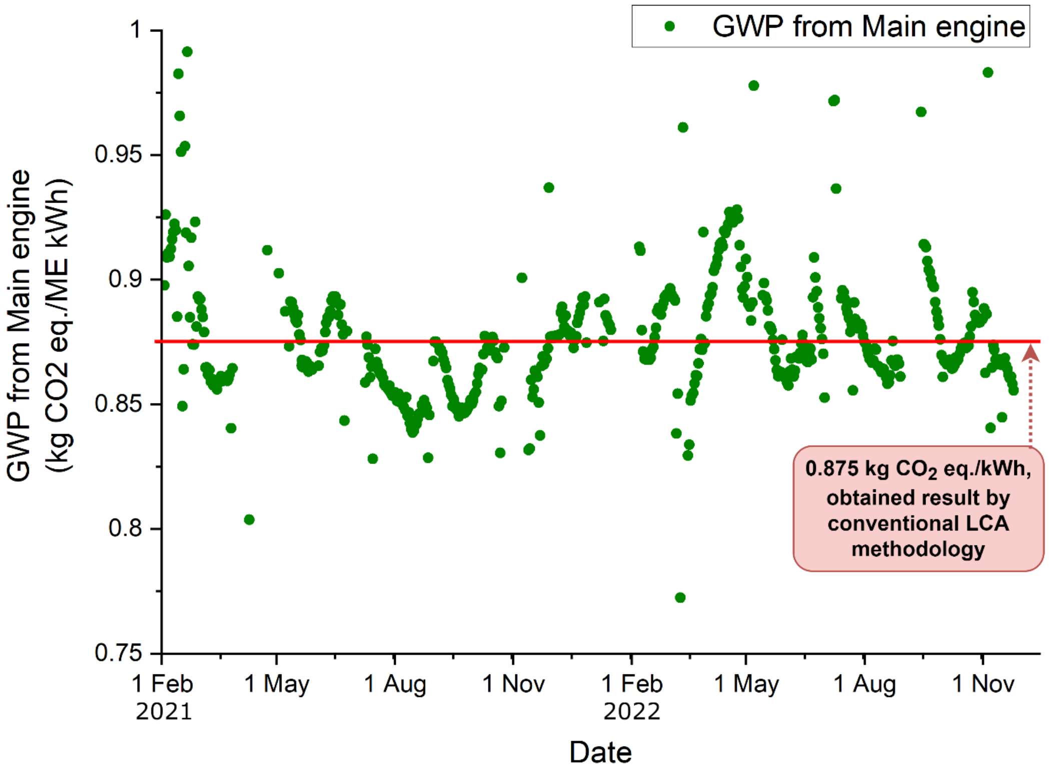


Figure 8-8. Results comparison between conventional LCA and RT-LCA

RT-LCA enables ship operators to comprehend/quantify the correlations between efficient operating practices and the reduction in holistic environmental impacts. In this context, another merit can be claimed to its availability to set up a target level so that ship operators can instantly detect any adverse outcomes, thereby diagnosing the causes and taking corrective actions. For example, it can be set up to 0.9 kg CO_2 eq./kWh max as a target range (marginally acceptable) in this case study. Then, official procedures can be established on how to mitigate outliers by corrective actions such as engine maintenance, hull/propeller cleaning or even bunkering for cleaner fuel sources.

8.7.2. Data library for various marine fuels

The case ship currently runs on HFO from Singapore in non-Emission Control Areas (ECA) and runs on MGO within the ECA. These bunkering data and histories were used for the case study. On the other hand, the case ship is subject to stringent environmental regulations in-not-too the distant future. Therefore, it should comply with certain targets of emission reductions from a lifecycle perspective. As a result, this vessel and the entire marine industry should encounter the transition of using marine fuels in a cleaner way.

The environmental impacts of two identical fuels may vary significantly depending on their production methods in the upstream stage. Therefore, it is important to investigate and database the emissions and environmental impact per unit of fuel according to the production area at the LCI stage. As shown in the ‘Calculation of environmental impact (WtW phase)’ part of Figure 8-1, the RT-LCA model used in this study can include various fuels and environmental factors according to the production sites of the fuel, for several scenarios.

In addition to fossil fuels such as HFO and MGO, which are currently mainly used in the shipping field, the RT-LCA model designed for this study can also be applied to zero-carbon fuels such as electric energy, hydrogen, and ammonia, and carbon neutral fuels such as methanol and biofuel. In other words, it can be applied immediately to greener fuels expected to be used in the maritime sector in the future. Furthermore, this model can be advised as a useful tool to intuitively check the difference in environmental impact from other fuels.

The maritime sector, which has difficulties in obtaining adequate data for LCA, can utilise cumulative data as a key database for future regulatory development/application.

8.8. Chapter summary and conclusions

After conducting a literature review, it was discovered that conventional LCA methods that rely on static analysis are not compatible with the dynamic status of the shipping industry. To address the limitations of existing LCAs and account for the varying conditions in the shipping environment, Real-Time LCA (RT-LCA) was proposed as one of the dynamic methodologies. In Chapter 8, it was demonstrated that RT-LCA is a viable solution for overcoming the challenges faced by existing methods.

RT-LCA is applicable when real-time data can be collected and analysed. By utilising data from ships and databases in real-time, it is possible to accurately and promptly evaluate the environmental impact. This enables the assessment to reflect the complex and ever-changing conditions of the shipping industry.

In addition, RT-LCA consistently produces precise environmental impact results. As discussed in section 4.1, conventional LCA methods are suited for evaluating static production processes and are not appropriate for the constantly changing conditions in the shipping industry. The limitations of existing methods have resulted in environmental impact assessments that do not reflect the complexities of the maritime industry.

RT-LCA continuously generates results based on data collected in real-time, enabling environmental impact assessments that are more suited to the shipping industry. This is a significant improvement over existing methods that produce only a single result. As demonstrated in the case study in Chapter 8, RT-LCA is an efficient and appropriate method for implementing LCA in the shipping industry. It provides immediate insights into the environmental impact, enabling more efficient operation of ships. Furthermore, fuel-saving plans can be established and environmental improvements can be quickly identified and implemented.

Moreover, RT-LCA is valuable for setting target ranges of environmental impacts, making it easy to verify compliance with various environmental regulations. This enhances the regulatory compliance of the shipping industry, improving its environmental performance.

9. DISCUSSION

9.1. Novelty and Contributions of research

The novelty of the research conducted in this thesis lies in the identification of the limitations of the existing environmental impact assessment methods and proposing an improved environmental impact assessment methodology (Dynamic LCA) that can overcome them. Since it was clearly recognised that applying the conventional LCA methodology to the shipping sector can be vastly challenging. The proposed ideas enable accurate and reliable environmental impact assessments of various fuel and energy sources, as well as activities in the maritime sector, from a holistic perspective. Furthermore, these suggestions for the new methodology can be extrapolated to other systems and situations, further enhancing the value of the research results. Furthermore, it serves as a crucial foundation and reference for establishing future regulations and policy frameworks.

9.1.1. Overcoming data dependence

This thesis has strong novelty through "Data generation" method, from Live-LCA (LLCA), which can make it possible to supplement the weaknesses of existing research and conduct reliable environmental evaluation research on ships using net-zero fuels. This opens up new practices and standards for future LCA research, providing significant benefits to enhance the quality and reliability of LCA studies with higher confidence.

The LLCA framework is believed to make sound contributions to improve LCA theory and practices, as well as extend the connection of LCA to different disciplines. This thesis establishes a new LCA standard, particularly in the marine industry. The thesis first considered the dynamic features of marine systems systematically, so that the relationships among the inputs and 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, considering real-time performance. It is also expected to offer effective information and guidelines for future maritime regulatory frameworks.

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

In addition to this, the case study results on marine fuels using Live-LCA can assist many governments, organisations, and companies in achieving their goals to increase low emission vessels in small and medium-sized fleets as part of their climate change suppression plans.

Therefore, this thesis can propose a roadmap to low carbon shipping while helping to deliver sustainable economic growth and secure the high competitiveness of the shipping sector. The research performance will be an excellent way to proceed with proposals for real applications towards high technology readiness levels. Thus, this thesis can fill the research gaps and suggest a new direction for environmental research in the shipping field and maritime LCA study. In addition, the numerous results of this thesis can be directly applied to actual industries and used as baseline data to evaluate the environmental properties of ships.

9.1.2. Overcoming static activity-based assessment

There is no doubt regarding the significance of LCA's implementation in the marine sector. This thesis proposes a direction for improving LCA in the marine sector by introducing the RT-LCA approach, which can be considered a new LCA standard specialised for industrial sectors engaged with dynamic processes. The proposed approach offers further insight into the IMO and EU Commission, which are striving to develop proper LCA guidelines for marine fuels. It is believed that the key research findings presented in this thesis will directly benefit these organisations in developing future regulatory frameworks.

The fundamental goal of this thesis is to suggest a credible solution for effectively applying the LCA technique to the global shipping sector, where hundreds of thousands of ships currently in service emitted 833 million tons of CO_2 in 2021, a 4.2% rise from 2019. This thesis highlights the key functionality of the RT-LCA, which can monitor fuel consumption and emissions in real-time through data communication, and can be a credible solution for more proactive and cleaner shipping.

On the other hand, onboard deck offices are currently required to estimate the CII level of the case ship annually using Equation (6).

$$\frac{CO_2\ emissions}{Deadweight \times Distance\ sailed} = Attained\ CII\ (g/ton\ mile) \tag{6}$$

As discussed earlier, the CII provides limited information on the environmental performance of the target vessel. In contrast, this thesis proposes the use of RT-LCA to enhance the existing CII by adding WtT elements and a holistic emission perspective into CII, which focuses only on TtW and CO_2 analysis as proposed in Equation (7).

$$\frac{WtW\ GWP}{Deadweight \times Distance\ sailed} = Attained\ CII\ (g/ton\ mile) \tag{7}$$

As environmental regulations become more stringent, vessels with poor energy efficiency are subject to additional energy costs and carbon taxes, making them an important competitive disadvantage for cargo contracts. In this context, shipping companies are increasingly relying on digital services that provide monitoring and management systems to estimate carbon emissions (and CII) and energy efficiency of ships to avoid restrictions on operation due to environmental regulations and secure carbon credits.

According to the EU Fuel Maritime Initiative (2021), the EU's marine emissions will be rigorously controlled at LCA levels by 2030. In this regard, the introduction of a standardised platform to quantify lifecycle emissions from ships and ports has become a top priority. In response to this transition, the development of a standardised maritime LCA model and platform has become an urgent task, which will address the exact challenges of decarbonising shipping. The digital LCA platform will provide a new horizon towards lifecycle maritime emission monitoring, reporting, and verification (MRV) as shown in Figure 9-1.

This thesis insightfully presents how a digital tool can effectively be used for real-time LCA analysis, offering a direction to develop a cutting-edge prototype digital platform for trustworthy and continuous lifecycle emissions monitoring and control for ships and ports. It is highly believed that RT-LCA can become a key element in providing a commercial prototype of a trustworthy, efficient, and lifecycle digital platform.

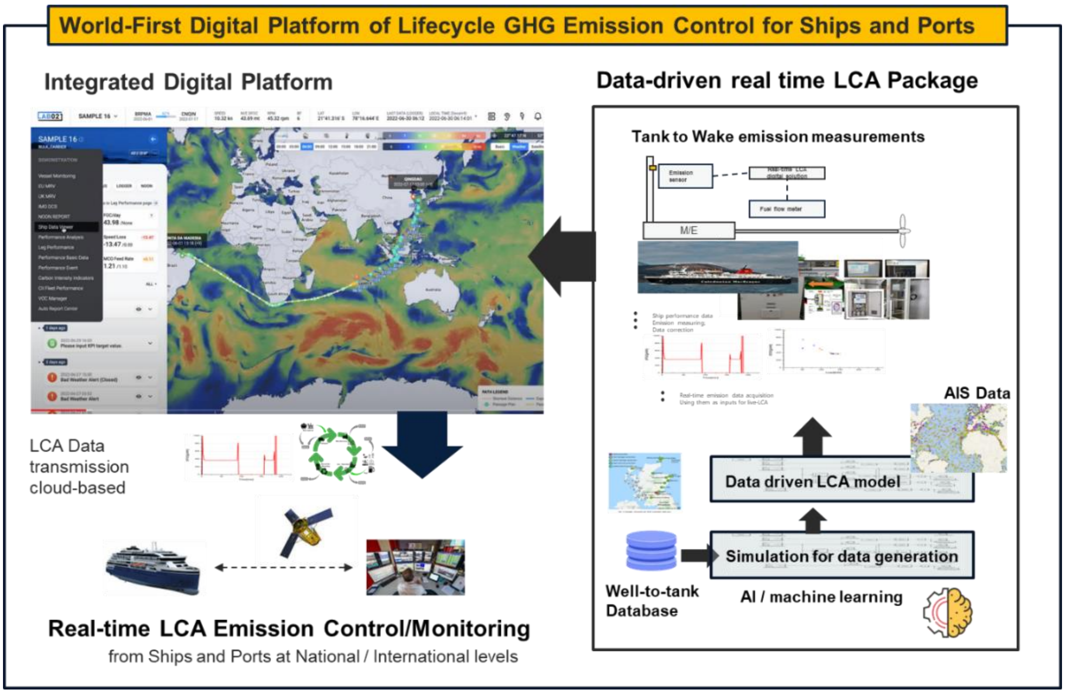


Figure 9-1. Conceptual outline of the digital platform for lifecycle GHG emission MRV

9.2. Limitations and the 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 thesis 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 thesis 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 optimisation. 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.

Moreover, one of the most effective ways to reinforce study results is actual verification. To conduct this work, it will be proposed to remodel a small vessel owned by the Scottish government, which is the case study target area in Chapter 7, to be put into research. This collaboration will create the next level of research proposal/collaboration that will be able to guide the way of evaluating technology for the UK's future plans/investments.

Through these next-level studies, the overcharging goal can be set up which is to maximise the usefulness of research outcomes to the maritime sector. That means, the direction for a true greener ship considering both local industry and infrastructure will be proposed and verified. It is expected that this will provide a basis for establishing appropriate policies to overcome the climate crisis and lay a foundation for continuous research that can contribute to more accurate and reliable carbon reduction in the shipping sector.

Furthermore, those results will be able to contribute to the proposal of policy (the IMO agenda), new business development and etc which can lead more likely to interaction and solidarity between the potential stakeholders and the academia.

Lastly, for reliable and robust validation, vast real-time environmental impacts will be identified by applying the RT-LCA technique to various ships by collaborating with a company that can transmit/receive/store ship operation data in real time. Based on this, one of the next steps of this research is to conduct more rigorous research that can provide more specific guides for the introduction of LCA in the shipping field. Such collaboration and efforts to apply RT-LCA can contribute to greening the shipping sector, which is a valuable step toward promoting carbon emission reduction by governments and protecting the environment for the next generation.

In addition to this, it is essential to secure basic data in order to introduce and utilise RT-LCA in the shipping field. So as to do a comprehensive analysis from the perspective of WtW, the production and refinery site and distribution process of the fuel used in ships are required, so a proposal is required to include the corresponding data in the Bunker Delivery Note (BDN).

This approach was intended to reduce the GHG footprint and encourage technologies and production pathways that provide tangible benefits over conventional fuels. Previous EU actions have already had a history of spurring a corresponding IMO response to GHG issues. From these precedents, the European Commission's proposed regulation is highly likely to have an impact on the IMO in the future, and it is expected that the IMO will develop a new Life Cycle Assessment (LCA) guideline to evaluate the well-to-wake perspective of fuels based on this regulation.

10. CONCLUSIONS

Based on the research work discussed in this thesis, the following conclusions can be drawn:

1) Current research that focuses solely on efficiency and emissions reduction from the user's perspective in order to assess the environmental impact of ship activities and contribute to environmental protection yields limited results. To identify areas for improvement from a holistic standpoint and develop comprehensive measures, the shipping industry must introduce Life Cycle Assessment (LCA), which takes into account the production stage as well.
2) Despite the desperate need for LCA in the shipping industry, upon reviewing its initial application and utilisation background, it was determined that it is not suitable for use in this field. Existing LCA has been applied and utilised based on systems that operate in unchanging environments, such as a company's production line, which allows for adequate evaluation with a single result in a static environment. In addition, data collection is straightforward as it targets a limited process, and environmental assessments are based solely on collectable data.
3) Given that the maritime industry operates in a constantly changing environment, the evaluation method for the shipping environment must be tailored to suit a dynamic system. Moreover, the database scope is vast, and a significant amount of data cannot be collected. Therefore, it is clear that the existing LCA cannot address the shipping sector.
4) In this study, it is proposed "Dynamic LCA" that can overcome the limitations of the conventional LCA and cover the dynamic environmental characteristics of the shipping industry. Live-LCA is one such methodology that supplements the data dependence of existing LCA. Instead of replacing unattainable data solely with assumptions and expectations, it enables reliable LCA research that is appropriate for the situation by performing "Data generation" through simulation or experimentation. Through this advanced LCA, the research methodology can be applied to a wide range of subjects,

and LCA results are not limited to the research vessel, allowing for general observation.

5) RT-LCA is another detailed methodology of dynamic LCA that can be used when real-time data can be collected. This makes it possible to perform LCA that immediately reflects the changing environment. In addition, since the environmental impact results are continuously derived, appropriate and suitable environmental impacts according to the dynamic environment can be continuously confirmed.
6) The results of the first case study in Chapter 6 using the Live-LCA methodology provide a different quantitative and intuitive perspective on whether electric propulsion ships are entirely green ships, which will be significantly useful for ship designers, owners, rule developers, and policymakers.
7) In the case study in Chapter 7, several alternative carbon-free fuels were studied to answer the question of what could be an appropriate energy solution for the shipping sector through the application of the Live-LCA methodology. Through the research process, it was confirmed that only the application of alternative fuels itself could not be beneficial in terms of environmental protection, and further technology development was necessary. Research through this methodology can contribute to improving the environmental effects in the maritime sector and suggest environmental guidelines that can be taken to achieve the International Maritime Organization's (IMO) final goal of zero CO_2.
8) The case study in Chapter 8 reveals that conventional LCA methods that rely on static analysis are incompatible with shipping operated in dynamic situations. The RT-LCA proposed in this thesis was shown to be an excellent solution to address current shortcomings. Therefore, RT-LCA provides a key to solving critical challenges head-on, and the concept of the methodology proposed in this case study can provide meaningful insights to rule-makers for future regulatory frameworks.
9) In this context, the proposed enhanced methodology not only provides insights for improving the environmental sustainability of ships, but also underscores the importance of approaching electric propulsion ships and

zero-carbon fuels from a life cycle assessment perspective. Additionally, as a study that can be applied to various ships, this methodology that can be used regardless of the scope of application was recommended for adoption towards cleaner shipping.

10) In conclusion, the implementation of the "Dynamic LCA" methodology proposed in this thesis is crucial for obtaining precise and comprehensive environmental impact assessments in the shipping industry, replacing the conventional LCA that is limited in its applicability. This approach allows for the identification of more suitable strategies to enhance the environment and enables long-term solutions rather than temporary measures. Moreover, the methodology provides valuable insights and a suitable framework for stakeholders, regulatory bodies, and policymakers in their efforts to achieve net-zero emissions in the shipping sector.

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A. Appendix for Chapter 3

Table A-1. Previous research regarding current measures in the maritime sector to increase efficiency and achieve net zero

Year	Research content	Category	Scope	Ref
~1800 s				
1730	Research related to using fuel	Fuel usage & feature	TtW	(Allen, 1730)
1865 1865	A study on applying petroleum, a liquid fuel, to a steam engine that used to use coal	Fuel usage & feature	TtW	(Paul, 1865) (Richardson, 1865)
1884	Choosing an appropriate fuel taking into account the characteristics of the place of use	Fuel usage & feature	TtW	(Clark, 1884)
1895	The advantages of liquid fuels such as petroleum over coal	Fuel usage & feature	TtW	(Edwards, 1895)
1900~1950				
1909	As fuel for ships, comparing coal with petroleum	Fuel usage & feature	TtW	(Blackiston, 1909)
1920	Background in which heavy oil began to be used and its advantages. Explaining the evolution of internal combustion engines through the use of heavy-oil	Engine & System related to fuel	TtW	(Verhey, 1920)
1921	The superiority of fuel oil in terms of users according to advantages and ships' characteristics	Fuel usage & feature	TtW	(Daniels, 1921)
1921 1928	Characteristics of the engine and fuels according to the engine	Engine & System related to fuel	TtW	(Lucke, 1921) (Evans and Brierly, 1928)
1929	Advantages and disadvantages based on the aspect of using liquid fuel and coal	Fuel usage & feature	TtW	(D'Eyncourt, 1929)
1944	Approaches to structural and design problems of fuel systems	Engine & System related to fuel	TtW	(Beck and Miller, 1944)
1951~2000				
1951	Phenomenons such as incompatibility and emulsification of fuel oil system, and evaluating fuel stability including incomplete combustion	Fuel usage & feature	TtW	(Martin, 1951)
1977	Initial reports of the use of hydrogen fuel for ships on a small 260 kW gas turbine	Alternative fuels	TtW	(Ford, 1977)

	installation experiment on a US Navy landing craft			
1985	A study on the correlation between fuel cost and shipbuilding and operating cost	Engine & System related to fuel	TtW	(Buxton, 1985)
1990	Marine exhaust emission quantification study	Environmental issue in the maritime sector	TtW	(Register, 1990)
1991	Effect of emulsified fuels in 4-stroke engines	Fuel usage & feature	TtW	(Harbach and Agosta, 1991)
1995	Describing the emulsification properties of fuels	Fuel usage & feature	TtW	(Lin et al., 1995a)
1995	The combustion properties of emulsified fuels	Fuel usage & feature	TtW	(Lin et al., 1995b)
1995	Marine exhaust emission quantification study	Environmental issue in the maritime sector	TtW	(Carlton et al., 1995)
1995	Discussing environmental regulations proposed by IMO	Environmental issue in the maritime sector	TtW	(Okamura, 1995)
1996	Effects of pollutants generated from ships focusing on sulfur oxides (SO_x) and nitrogen oxides (NO_x)	Environmental issue in the maritime sector	TtW	(Kütting and Gauci, 1996)
1997	Showing that ships are a major cause of air pollution and discussing policy implications	Environmental issue in the maritime sector	TtW	(Corbett and Fischbeck, 1997)
1997	Reviewing the application of nuclear-powered vessels to the arctic icebreaker	Alternative fuels	TtW	(Khlopkin and Zotov, 1997)
1999	Problems of emissions from the combustion of marine fuels, such as SO_x and particulate matter (PM)	Environmental effect from fuel	TtW	(Capaldo et al., 1999)
1999	Needs for policy formulation to reduce various damages caused by NO_x	Environmental issue in the maritime sector	TtW	(Lawrence and Crutzen, 1999)
2000	Studying the effects of temperature and water in terms of biodeterioration of fuel	Fuel usage & feature	TtW	(Chung et al., 2000)
2000	A study to reduce emissions through fuel saving by improving the propulsion characteristics of ships	Efficiency for environment	TtW	(Stefanopoulou and Smith, 2000)
2000	Research on shipbuilding such as hull design, corrosion prevention, and hull material from a life cycle perspective regarding environmental impact and economical operation	Efficiency for environment	TtW	(Hayman et al., 2000)
2000	Project to use natural gas as fuel on US coastline	Alternative fuels	TtW	(Farrell and Glick, 2000)
2001~2010				

2001	The difference in emission when installing different types of engines or emission reduction devices such as selective catalytic reduction (SCR)	Devices for environment	TtW	(Cooper, 2001)
2002 2002	Research on ships powered by electricity and motors instead of conventional fuel and propulsion systems	Alternative fuels	TtW	(Calfo et al., 2002) (McCoy, 2002)
2003	Investigation of emissions from ships and their resulting environmental impact	Environmental issue in the maritime sector	TtW	(Endresen et al., 2003)
2004	A study on energy conservation and energy consumption trends in marine transportation	Environmental effect from fuel	TtW	(Corbett, 2004)
2004	Research to reduce the fuel consumption from hull forms, microbubbles, hull coating, hull weight reduction, and propulsion system efficiency improvement	Efficiency for environment	TtW	(Seif and Tavakoli, 2004)
2005	Analysis of effects such as ignition and combustion quality according to ship fuels	Fuel usage & feature	TtW	(Forget, 2005)
2006	Analysing and improving the impact of ship's pollutant emissions on the coast	Environmental issue in the maritime sector	TtW	(Delft et al., 2006)
2006	Comparison of environmental impact from LCA perspective when molten carbonate fuel cell (MCFC) and diesel engine (DE) are applied to a ship	LCA study in the maritime sector	WtW	(Alkaner and Zhou, 2006)
2007	Collecting and organising historical records of fuel consumption and emissions from ships	Environmental effect from fuel	TtW	(Endresen et al., 2007)
2007	Comparing the costs of optimal emission reduction and the control	Environmental issue in the maritime sector	TtW	(Cofala et al., 2007)
2007	A study on the environmental benefits of using hydrogen in ships	Alternative fuels	TtW	(Veldhuis et al., 2007)
2007	Developed LCA methodology which called ‘LIME’	LCA study in the maritime sector	WtW	(Kameyama et al., 2007)
2008	Proposing a system optimisation method to increase the economic efficiency and cost-efficiency	Efficiency for environment	TtW	(Dimopoulos et al., 2008)
2008	Proposal of the voyage and vessel optimisation system	Efficiency for environment	TtW	(Ballou et al., 2008)

	(VVOS) to reduce GHG emissions			
2008	Conducting research on ships powered by LNG to reduce emissions from ships such as CO_2, NO_x, SO_x and PM	Alternative fuels	TtW	(Brett, 2008)
2009	Differences in emissions depending on the fuel used by vessels	Environmental effect from fuel	TtW	(Winnes and Fridell, 2009)
2009	Emissions from ships depending on the fuel, and their environmental impact	Environmental effect from fuel	TtW	(Dalsøren et al., 2009)
2009	Environmental and health impacts of PM in exhaust gases from HFO-fuelled diesel engines	Environmental effect from fuel	TtW	(Moldanová et al., 2009)
2009	Environmental impacts and possible consequences from emissions when HFO is used	Environmental effect from fuel	TtW	(Popovicheva et al., 2009)
2009	A study to improve fuel efficiency using Energy Storage System (ESS) and diesel engine generator	Devices for environment	TtW	(Gully et al., 2009)
2009	Presenting the concept of a combined large-power ship propulsion system consisting of the power gas turbine and the steam turbine system, with the diesel main engine	Devices for environment	TtW	(Dzida et al., 2009)
2010	Engine efficiency determines power specific fuel consumption and vessel speed is important for ton-mile specific fuel consumption	Engine & System related to fuel	TtW	(Shi et al., 2010)
2010	Investigating and organising emission factors when HFO is used, and providing a comprehensive outlook on pollutants generated from ships	Environmental effect from fuel	TtW	(Agrawal et al., 2010)
2010	Current status of pollution mitigation measures implemented in the shipping sector	Environmental issue in the maritime sector	TtW	(Han, 2010)
2010	Research of hybrid system that combines a diesel engine and an electric energy storage system to reduce fuel consumption and emissions of ships	Devices for environment	TtW	(Dedes et al., 2010)
2010	Environmental and economic benefits of changing diesel oil used in ships to natural gas	Alternative fuels	TtW	(Banawan et al., 2010)

2010	Evaluation of Solid Oxide Fuel Cells (SOFC) fuelled by methanol from an LCA perspective	LCA study in the maritime sector	WtW	(Strazza et al., 2010)
2011~				
2012	Applying shaft generator system to the shaft of main engine	Devices for environment	TtW	(Prousalidis et al., 2012)
2012	Investigating energy consumption and GHGs of SOx regarding scrubber system	LCA study in the maritime sector	WtW	(Ma et al., 2012)
2014	LCA for ocean-going vessels	LCA study in the maritime sector	WtW	(Chatzinikolaou and Ventikos, 2014)
2015	Considering future fuels of ships in various aspects such as availability, renewability, safety, cost, performance, economics and emission regulation	Alternative fuels	TtW	(Elgohary et al., 2015)
2015	Presenting an overall framework for analysing ship emissions from the point of view of the life cycle	LCA study in the maritime sector	WtW	(Chatzinikolaou and Ventikos, 2015)
2016	Conducting research to validate fuel oil additives used to increase fuel efficiency and reduce emissions	Efficiency for environment	TtW	(Jang and Choi, 2016)
2016	Presenting step modulation strategy of the power system to reduce thrust loss and increase fuel efficiency	Efficiency for environment	TtW	(Zhao et al., 2016)
2016	Presenting an overall framework for analysing ship emissions from the point of view of the life cycle	LCA study in the maritime sector	WtW	(Chatzinikolaou and Ventikos, 2016)
2016	Evaluating the environmental impact of the hybrid system consisting of the lithium-ion battery, the solar system and the cold-ironing system from the life cycle perspective	LCA study in the maritime sector	WtW	(Ling-Chin and Roskilly, 2016b)
2016	Investigating the total environmental benefits of power systems from the life cycle perspective	LCA study in the maritime sector	WtW	(Ling-Chin and Roskilly, 2016a)
2017	Proposing Mean Value First Principle (MVFP) propulsion model to reduce fuel consumption and achieve emission reduction	Devices for environment	TtW	(Geertsma et al., 2017b)

2017	Adopting battery energy storage systems (BESS) and presenting parameter identification method	Devices for environment	TtW	(Misyris et al., 2017)
2017	Establishing an improved control strategy to optimally operate a hybrid propulsion system combining mechanical and electrical propulsion systems	Efficiency for environment	TtW	(Geertsma et al., 2017a)
2017	A review of previous studies in various aspects such as hull design, power & propulsion, speed, fuels, energy sources, and operation routine & schedule on how to reduce GHG emissions	Efficiency for environment	TtW	(Bouman et al., 2017)
2017	Applying the life cycle carbon emission evaluation method and deriving optimum energy/carbon efficiency	LCA study in the maritime sector	WtW	(Nian and Yuan, 2017)
2018	Conducting studies to replace Internal Combustion Engines (ICEs) with Gas Turbines (GTs) with lower NOx emissions to meet tightening IMO regulations	Devices for environment	TtW	(Armellini et al., 2018)
2018	Proposing B/FW HESS, a combined Battery and Flywheel Hybrid Energy Storage System	Devices for environment	TtW	(Hou et al., 2018)
2018	Periodic hull cleaning	Efficiency for environment	TtW	(Adland et al., 2018)
2018	Proposing energy management, including statistical analysis and modelling, of the engine	Efficiency for environment	TtW	(Tsitsilonis and Theotokatos, 2018)
2018	Energy-efficient operation test using a full-mission simulator	Efficiency for environment	TtW	(Jensen et al., 2018)
2018	Comprehensive review of biodiesel fuel	Alternative fuels	TtW	(Noor et al., 2018)
2018	Performing LCA on alternative fuels such as LNG, methanol, hydrogen, and biodiesel that can be used on ships	LCA study in the maritime sector	WtW	(Gilbert et al., 2018)
2019	Summarising and analysing the application of AMP	Devices for environment	TtW	(Chen et al., 2019)
2019	Minimising power consumption through slow steaming operation	Efficiency for environment	TtW	(Dere and Deniz, 2019)
2019	Optimisation of navigation speed between ports through artificial neural network model	Efficiency for environment	TtW	(Zheng et al., 2019)
2019	Presenting emission differences between several types of fuels	Alternative fuels	TtW	(Van et al., 2019)

	such as MGO, LNG and biofuels			
2019	Study about power generation by steam turbines, gas turbines, internal combustion engines and fuel cells fuelled by ammonia	Alternative fuels	TtW	(De Vries, 2019)
2019	Study of total 7 fuels, liquefied natural gas (LNG), liquefied biogas (LBG), methanol from natural gas, renewable methanol, hydrogen for fuel cells, hydrotreated vegetable oil (HVO) and heavy fuel oil (HFO), using a multi-criteria decision analysis technique	Alternative fuels	TtW	(Hansson et al., 2019)
2019	Investigating methanol-diesel dual fuel	Alternative fuels	TtW	(Ammar, 2019)
2019	LCA study for the environmental impact of HFO and LNG used as ship fuel	LCA study in the maritime sector	WtW	(Sharafian et al., 2019)
2019	Comparing environmental impacts between MGO and LNG fuels of shipping	LCA study in the maritime sector	WtW	(Hwang et al., 2019)
2019	Analysing the GHG emissions of HFO and MGO produced from Saudi crude oil compared to LNG from various regions in terms of LCA	LCA study in the maritime sector	WtW	(El-Houjeiri et al., 2019)
2019	LCA study for a ferry applying Solar PV system	LCA study in the maritime sector	WtW	(Wang et al., 2019)
2020	Applying 7 types of fuel cells and analysing based on 8 criteria	Devices for environment	TtW	(Inal and Deniz, 2020)
2020	Solution for Recovery of Cold Energy of LNG	Efficiency for environment	TtW	(Baldasso et al., 2020)
2020	Analysing Carbon Footprint (CF) and applying various trials; speed reduction, using wind/solar energy, LNG	Efficiency for environment	TtW	(Ančić et al., 2020)
2020	Study of sustainability of LNG from the perspective of environmental impact, economics and intrinsic safety of the fuel system	Alternative fuels	TtW	(Iannaccone et al., 2020)
2020	A study on fuel consumption and emission changes in each case of changing the fuel to LNG and changing the propulsion system to a hybrid type	Alternative fuels	TtW	(Sui et al., 2020)
2020	Study of power system integration, control, safety and	Alternative fuels	TtW	(Shakeri et al., 2020)

	related regulations with hydrogen fuel cells (FCs) as the main power source			
2020	Proposing a direction to improve high NO_x and N_2O emissions that may occur from ammonia fuel through optimal combustion and post-treatment system	Alternative fuels	TtW	(Zincir, 2020)
2020	Conducting research on the use of ammonia as fuel in conventional internal combustion engines	Alternative fuels	TtW	(Dimitriou and Javaid, 2020)
2020	Identifying applicable energy systems of electric propulsion ships and resenting energy efficiency	Alternative fuels	TtW	(Nuchturee et al., 2020)
2020	Conducting a case-by-case study on the use of various fuels such as electricity, methanol, dimethyl ether, natural gas, hydrogen and biodiesel by LCA and LCCA	LCA study in the maritime sector	WtW	(Perčić et al., 2020)
2020	Investigating the environmental advantages of a Ro-Ro ship with the battery system	LCA study in the maritime sector	WtW	(Jeong et al., 2020)
2020	Conducting LCA for scrubber system of shipping with introducing a new methodology ‘PT-LCA’	LCA study in the maritime sector	WtW	(Jang et al., 2020)
2021	A study for the difference in the amount of emissions depending on the operating load of the engine using HFO as fuel	Environmental effect from fuel	TtW	(Zhang et al., 2021)
2021	Confirmation of fuel savings and efficiency by applying Wind-assisted ship propulsion (WASP) technology to ships	Devices for environment	TtW	(Chou et al., 2021)
2021	A study on the correlation between speed reduction and energy efficiency/environmental benefit	Efficiency for environment	TtW	(Elkafas and Shouman, 2021)
2021	Proposing a model using two power sources, an internal combustion engine (ICE) and a molten carbonate fuel cell (MCFC) as a hybrid propulsion system using LNG as fuel in terms of system efficiency	Alternative fuels	TtW	(Baccioli et al., 2021)
2021	A study of a ship's power system combining solid oxide fuel cell (SOFC) and internal	Alternative fuels	TtW	(Sapra et al., 2021)

	combustion engine (ICE) in terms of efficiency and emission			
2021	Discussing hydrogen storage	Alternative fuels	TtW	(Van Hoecke et al., 2021)
2021	Research in terms of feasibility, environmental impact, and operational viability on liquefied natural gas, hydrogen, and ammonia	Alternative fuels	TtW	(Al-Enazi et al., 2021)
2021	Proposing a new methodology called PT-LCA that compensates for the shortcomings of the existing LCA with consideration of LNG fuel	LCA study in the maritime sector	WtW	(Jang et al., 2021)
2021	Analysing hydrogen, ammonia, biofuels, methanol, LNG, and LPG as alternative fuels	LCA study in the maritime sector	WtW	(Xing et al., 2021)
2021	Providing assessment of hydrogen as fuel in terms of economic, technical, and safety aspects	LCA study in the maritime sector	WtW	(Atilhan et al., 2021)
2021	Study of environmental impacts for main marine fules (HFO, LFO, VLSFO, ULSFO)	LCA study in the maritime sector	WtW	(Bilgili, 2021)
2022	Designing and proposing power-split control systems using machine learning techniques	Efficiency for environment	TtW	(Planakis et al., 2022)
2022	Proposing multi-populations particle swarm optimisation (MPPSO) in order to optimise the energy storage system (ESS), photovoltaic cell (PV) and generator constituting the hybrid power ship system (HPSS) in terms of efficiency, environmental effects and operating cost	Devices for environment	TtW	(Xu et al., 2022)
2022	Analysing optimal design for waste heat recovery and utilisation	Devices for environment	TtW	(Konur et al., 2022)
2022	Applying diesel-electric propulsion system instead of diesel engine propulsion system	Devices for environment	TtW	(Elkafas and Shouman, 2022)
2022	Analysing slow steaming and the relationship between ship speed and fuel consumption	Efficiency for environment	TtW	(Farkas et al., 2022)
2022	Studying increase fuel efficiency through emissions management, fuel conversion, and power conversion	Efficiency for environment	TtW	(Mohammad Danil and Fanny, 2022)

2022	Developing multi-objective mathematical model by collaboration of shipping routes and terminals	Efficiency for environment	TtW	(Dulebenets, 2022)
2022	Figuring out the correlation between voyage plan and energy efficiency	Efficiency for environment	TtW	(Poulsen et al., 2022)
2022	Proposal of strategies to reduce GHG emissions by optimally operating diesel engines (DEs), hydrogen with fuel cells (FCs) and electricity with batteries	Alternative fuels	TtW	(Fan et al., 2022)
2022	Considering Liquefied petroleum gas (LPG) as a bridge fuel for the transition to zero-carbon fuel	Alternative fuels	TtW	(Yeo et al., 2022)
2022	Conventional fuels used in the bulk carrier were compared to ammonia by Techno-Economic analysis	Alternative fuels	TtW	(Ejder and Arslanoğlu, 2022)
2022	Study of holistic environmental pros and cons of the electric propulsion ship by comparing 14 primary energy sources for production and 33 national cases	LCA study in the maritime sector	WtW	(Jeong et al., 2022)
2022	Investigating environmental impacts of hydrogen fuel cells for shipping from the lifecycle perspective including hydrogen production and fuel cell types	LCA study in the maritime sector	WtW	(Jang et al., 2022)
2022	Environmental and cost study of various types of fuel cells using hydrogen and ammonia as fuels through LCA and LCCA	LCA study in the maritime sector	WtW	(Perčić et al., 2022)

Table A-2. Literature review of ships using Solar PV

Main Subject & Outcome	Methodology	Power source	Key point	Ref.
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	(Lee et al., 2013)
Solar PV system applying to the ship can make a	Cost-benefit analysis	Solar PV panel	Cost	(Glykas et al., 2010)

reduction in fuel consumption. Cost-effectiveness of the PV system depends on fuel price and the vessel sailing route.				
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	(Kaisha and Kyokai, 2011)
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	(George and Mihaela, 2014)
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 utilisation plan	(Rivela et al., 2015)
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	(Peng et al., 2014)
Suggesting the algorithm to find the ideal size of Solar PV system, ESS and Diesel generator	Multi-Objective Particle Swarm Optimisation (MOPSO)	Solar PV panel, Diesel generator, Energy storage system	Proper sizing of devices	(Lan et al., 2015)
Route optimisation is very important for energy efficiency. For solar ship, meteorological factor is the main thing to consider.	Route optimisation based on genetic algorithm	Solar PV panel	Efficiency	(Zhang et al., 2017)
Contributing to layout out of large-scale Solar PV panels and MPPT controlling method on ship.	Designing topology structure of the solar panel array	Solar PV panel, Energy storage system	Structure, Efficiency	(Tang, 2017)

	and algorithm of MPPT			
Applying solar energy system to ship can cut by 4.02% of fuel consumption and by 8.55% of CO_2 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	(Yuan et al., 2018a)
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	(Yuan et al., 2018b)
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	(Vahabzad et al., 2021)
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	(Atodiresei et al., 2017)

B. Appendix for Chapter 6

Table B-1. Solar data of each country for case study in Chapter 6

Australia				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (℃)
Jan	13.63	6.60	484.108	24.9
Feb	13.02	5.88	451.613	24.6
Mar	12.25	5.20	424.490	23.3
Apr	11.43	4.01	350.729	20.9
May	10.78	3.21	297.866	18.1
Jun	10.45	3.16	302.392	15.3
Jul	10.60	3.33	314.052	14.5
Aug	11.17	4.30	384.960	15.4
Sep	11.93	5.38	450.964	18.1
Oct	12.74	5.83	457.614	20.4
Nov	13.46	6.42	477.087	22.1
Dec	13.82	6.67	482.517	23.9

Belgium				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (℃)
Jan	8.49	0.85	100.078	4.6
Feb	10.03	1.59	158.524	4.5
Mar	11.92	2.78	233.287	6.6
Apr	13.88	4.36	314.046	8.9
May	15.57	5.46	350.749	12.4
Jun	16.45	5.74	348.936	15.2
Jul	16.00	5.62	351.250	17.8
Aug	14.50	4.91	338.621	18.2
Sep	12.60	3.25	257.937	15.5
Oct	10.67	1.91	179.007	12.4
Nov	8.93	0.99	110.862	8.2
Dec	8.03	0.60	74.720	5.5

Bulgaria				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (℃)
Jan	9.49	1.59	167.545	2.3
Feb	10.58	2.37	224.008	3.0
Mar	11.95	3.29	275.314	6.0
Apr	13.39	4.38	327.110	10.6
May	14.60	5.52	378.082	15.7

Jun	15.21	6.13	403.024	20.3
Jul	14.90	6.29	422.148	22.9
Aug	13.84	5.51	398.121	22.7
Sep	12.47	4.30	344.828	18.9
Oct	11.05	2.70	244.344	13.6
Nov	9.80	1.72	175.510	7.8
Dec	9.17	1.30	141.767	3.6
Brazil				
Month	Daytime (Hours)	Solar radiation ($kWh/m^2/d$)	Irradiance (W/m^2)	Temperature (°C)
Jan	12.31	5.74	466.288	27.9
Feb	12.22	5.54	453.355	27.8
Mar	12.12	5.04	415.842	27.3
Apr	12.02	4.77	396.839	27.1
May	11.95	5.17	432.636	27.3
Jun	11.91	5.26	441.646	26.9
Jul	11.93	5.70	477.787	26.7
Aug	11.99	6.42	535.446	27.0
Sep	12.09	6.76	559.140	27.3
Oct	12.19	6.92	567.678	27.6
Nov	12.29	6.56	533.767	27.9
Dec	12.33	6.22	504.461	28.1
Cyprus				
Month	Daytime (Hours)	Solar radiation ($kWh/m^2/d$)	Irradiance (W/m^2)	Temperature (°C)
Jan	10.12	2.73	269.763	11.8
Feb	10.94	3.68	336.380	11.8
Mar	11.98	5.03	419.866	13.7
Apr	13.08	6.25	477.829	17.4
May	13.98	7.42	530.758	21.3
Jun	14.44	8.27	572.715	25.0
Jul	14.21	8.02	564.391	27.4
Aug	13.42	7.31	544.709	27.7
Sep	12.38	6.18	499.192	25.6
Oct	11.30	4.58	405.310	22.0
Nov	10.36	3.17	305.985	17.0
Dec	9.89	2.46	248.736	13.4
Germany				
Month	Daytime (Hours)	Solar radiation ($kWh/m^2/d$)	Irradiance (W/m^2)	Temperature (°C)
Jan	8.05	0.50	62.112	0.5
Feb	9.79	1.11	113.381	0.6

Mar	11.89	2.28	191.758	2.8
Apr	14.09	3.83	271.824	6.6
May	16.00	5.27	329.375	11.6
Jun	17.02	5.57	327.262	15.0
Jul	16.50	5.24	317.576	17.6
Aug	14.79	4.44	300.203	17.6
Sep	12.67	2.89	228.098	14.2
Oct	10.52	1.58	150.190	10.0
Nov	8.56	0.67	78.271	5.2
Dec	7.52	0.38	50.532	1.7
Denmark				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (℃)
Jan	7.93	0.64	80.706	1.8
Feb	9.72	1.33	136.831	1.5
Mar	11.89	2.41	202.691	3.0
Apr	14.15	3.81	269.258	6.5
May	16.12	5.18	321.340	11.2
Jun	17.18	5.06	294.529	14.3
Jul	16.64	4.99	299.880	16.9
Aug	14.87	4.29	288.500	17.0
Sep	12.68	2.70	212.934	14.0
Oct	10.47	1.43	136.581	10.6
Nov	8.45	0.75	88.757	6.2
Dec	7.38	0.50	67.751	3.4
Estonia				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (℃)
Jan	7.25	0.48	66.207	-3.5
Feb	9.37	1.20	128.068	-4.4
Mar	11.86	2.51	211.636	-1.1
Apr	14.46	3.89	269.018	4.9
May	16.78	5.46	325.387	11.3
Jun	18.09	5.75	317.855	15.3
Jul	17.42	5.44	312.285	18.1
Aug	15.30	4.35	284.314	16.9
Sep	12.78	2.75	215.180	11.9
Oct	10.24	1.36	132.813	7.0
Nov	7.88	0.62	78.680	1.5
Dec	6.58	0.32	48.632	-1.8
Spain				
Month	Daytime	Solar radiation	Irradiance	Temperature

	(Hours)	(kWh/m^2/d)	(W/m^2)	(°C)
Jan	9.76	2.25	230.533	10.2
Feb	10.73	3.26	303.821	11.2
Mar	11.97	4.21	351.713	12.8
Apr	13.26	5.59	421.569	14.7
May	14.34	6.06	422.594	17.9
Jun	14.88	6.75	453.629	21.7
Jul	14.60	6.64	454.795	24.7
Aug	13.66	6.02	440.703	24.9
Sep	12.42	4.67	376.006	22.6
Oct	11.15	3.45	309.417	18.2
Nov	10.04	2.43	242.032	13.5
Dec	9.47	1.96	206.969	10.5

Finland

Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (°C)
Jan	6.82	0.27	39.589	-6.9
Feb	9.16	0.89	97.162	-6.8
Mar	11.85	2.09	176.371	-2.9
Apr	14.65	3.59	245.051	2.9
May	17.20	5.25	305.233	9.9
Jun	18.68	5.87	314.240	14.9
Jul	17.92	5.51	307.478	16.6
Aug	15.57	4.12	264.611	15.0
Sep	12.83	2.40	187.062	10.0
Oct	10.10	1.04	102.970	5.4
Nov	7.53	0.33	43.825	0.1
Dec	6.08	0.14	23.026	-4.1

France

Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (°C)
Jan	8.82	1.00	113.379	6.2
Feb	10.21	1.71	167.483	6.1
Mar	11.93	2.76	231.350	8.1
Apr	13.72	3.95	287.901	9.5
May	15.24	4.93	323.491	12.6
Jun	16.03	5.41	337.492	15.1
Jul	15.63	5.30	339.091	17.6
Aug	14.28	4.69	328.431	18.0
Sep	12.56	3.39	269.904	16.0
Oct	10.79	2.01	186.284	13.1
Nov	9.22	1.21	131.236	9.5
Dec	8.41	0.83	98.692	7.3

UK				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (°C)
Jan	8.55	0.90	105.263	6.2
Feb	10.06	1.64	163.022	6.1
Mar	11.92	2.70	226.510	7.6
Apr	13.86	4.21	303.752	9.3
May	15.52	5.36	345.361	12.9
Jun	16.39	5.64	344.112	15.4
Jul	15.94	5.55	348.181	17.7
Aug	14.46	4.79	331.259	18.0
Sep	12.60	3.30	261.905	15.7
Oct	10.69	1.95	182.413	12.6
Nov	8.98	1.08	120.267	9.0
Dec	8.09	0.68	84.054	6.7
Greece				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (°C)
Jan	9.88	2.14	216.599	9.9
Feb	10.80	2.88	266.667	9.8
Mar	11.97	4.00	334.169	11.7
Apr	13.20	5.37	406.818	15.2
May	14.21	6.43	452.498	19.9
Jun	14.73	7.46	506.449	24.7
Jul	14.47	7.36	508.639	27.6
Aug	13.58	6.62	487.482	27.6
Sep	12.41	5.21	419.823	24.0
Oct	11.20	3.44	307.143	19.2
Nov	10.15	2.18	214.778	14.6
Dec	9.62	1.73	179.834	11.2
Ireland				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (°C)
Jan	8.18	0.64	78.240	5.4
Feb	9.86	1.17	118.661	5.3
Mar	11.90	2.17	182.353	6.7
Apr	14.03	3.42	243.763	8.0
May	15.87	4.17	262.760	10.7
Jun	16.85	4.64	275.371	13.4
Jul	16.35	4.72	288.685	15.4
Aug	14.70	3.67	249.660	15.0
Sep	12.65	2.78	219.763	13.1

Oct	10.56	1.58	149.621	10.4
Nov	8.66	0.78	90.069	7.5
Dec	7.67	0.47	61.278	6.1
India				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (℃)
Jan	11.21	4.89	436.218	24.1
Feb	11.57	5.69	491.789	25.7
Mar	12.04	6.36	528.239	27.7
Apr	12.54	6.69	533.493	29.0
May	12.95	6.17	476.448	30.2
Jun	13.16	4.64	352.584	29.8
Jul	13.06	4.20	321.593	28.6
Aug	12.70	4.19	329.921	28.5
Sep	12.23	4.38	358.136	28.5
Oct	11.74	4.60	391.823	27.9
Nov	11.32	4.49	396.643	26.2
Dec	11.11	4.58	412.241	24.3
Italy				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (℃)
Jan	9.73	1.90	195.272	10.0
Feb	10.72	2.84	264.925	9.9
Mar	11.97	3.98	332.498	11.3
Apr	13.27	4.75	357.950	13.9
May	14.36	5.90	410.864	18.3
Jun	14.91	6.69	448.692	22.3
Jul	14.64	6.69	456.967	25.4
Aug	13.68	5.80	423.977	25.6
Sep	12.43	4.61	370.877	22.3
Oct	11.14	2.99	268.402	18.7
Nov	10.01	2.27	226.773	14.5
Dec	9.44	2.07	219.280	11.3
Japan				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (℃)
Jan	10.06	3.00	298.211	6.0
Feb	10.90	3.72	341.284	6.3
Mar	11.97	4.17	348.371	9.1
Apr	13.10	4.88	372.519	14.3
May	14.03	4.85	345.688	18.5
Jun	14.51	4.21	290.145	21.6

Jul	14.28	4.43	310.224	25.1
Aug	13.47	4.47	331.849	26.9
Sep	12.39	3.31	267.151	23.5
Oct	11.29	3.05	270.151	18.3
Nov	10.31	2.77	268.671	13.4
Dec	9.82	2.72	276.986	8.6
Lithuania				
Month	Daytime (Hours)	Solar radiation ($kWh/m^2/d$)	Irradiance (W/m^2)	Temperature (°C)
Jan	7.78	0.62	79.692	-1.2
Feb	9.64	1.29	133.817	-1.4
Mar	11.88	2.68	225.589	1.2
Apr	14.22	4.18	293.952	6.1
May	16.26	5.83	358.549	11.2
Jun	17.37	6.03	347.150	14.3
Jul	16.81	5.87	349.197	17.6
Aug	14.96	4.88	326.203	17.7
Sep	12.71	3.16	248.623	13.5
Oct	10.42	1.61	154.511	9.0
Nov	8.33	0.74	88.836	3.7
Dec	7.21	0.49	67.961	0.6
Latvia				
Month	Daytime (Hours)	Solar radiation ($kWh/m^2/d$)	Irradiance (W/m^2)	Temperature (°C)
Jan	7.55	0.33	43.709	-4.7
Feb	9.52	0.72	75.630	-4.2
Mar	11.87	2.09	176.074	-0.5
Apr	14.32	3.14	219.274	5.1
May	16.49	4.94	299.576	11.4
Jun	17.68	5.13	290.158	15.5
Jul	17.08	5.15	301.522	16.9
Aug	15.11	3.86	255.460	16.2
Sep	12.74	2.27	178.179	12.0
Oct	10.34	1.15	111.219	7.4
Nov	8.13	0.38	46.740	2.1
Dec	6.94	0.22	31.700	-2.3
Malta				
Month	Daytime (Hours)	Solar radiation ($kWh/m^2/d$)	Irradiance (W/m^2)	Temperature (°C)
Jan	10.05	2.57	255.721	11.5
Feb	10.90	3.50	321.101	12.4
Mar	11.98	4.88	407.346	13.7

Apr	13.11	5.83	444.699	15.8
May	14.05	7.12	506.762	19.8
Jun	14.52	7.66	527.548	23.1
Jul	14.29	7.78	544.437	26.9
Aug	13.46	6.97	517.831	26.6
Sep	12.38	5.53	446.688	24.2
Oct	11.27	4.07	361.136	21.3
Nov	10.30	2.88	279.612	17.6
Dec	9.81	2.33	237.513	13.6
Netherlands				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (℃)
Jan	8.31	0.77	92.659	2.9
Feb	9.93	1.46	147.029	1.9
Mar	11.91	2.62	219.983	5.4
Apr	13.97	4.11	294.202	8.4
May	15.75	5.50	349.206	12.7
Jun	16.69	5.55	332.534	14.9
Jul	16.21	5.42	334.362	17.8
Aug	14.62	4.71	322.161	17.4
Sep	12.63	3.01	238.321	14.6
Oct	10.61	1.66	156.456	10.9
Nov	8.78	0.86	97.950	6.4
Dec	7.82	0.54	69.054	4.4
Norway				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (℃)
Jan	7.07	0.39	55.163	0.6
Feb	9.28	1.09	117.457	0.2
Mar	11.86	2.31	194.772	1.7
Apr	14.54	3.70	254.470	5.3
May	16.96	5.32	313.679	10.7
Jun	18.34	5.54	302.072	14.8
Jul	17.63	5.51	312.535	17.4
Aug	15.41	4.23	274.497	17.2
Sep	12.80	2.76	215.625	13.5
Oct	10.18	1.30	127.701	9.3
Nov	7.73	0.54	69.858	5.0
Dec	6.37	0.24	37.677	2.4
New Zealand				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (℃)

Jan	14.78	6.36	430.311	16.6
Feb	13.70	5.54	404.380	16.9
Mar	12.36	4.45	360.032	15.8
Apr	10.97	3.12	284.412	14.0
May	9.83	2.15	218.718	12.7
Jun	9.25	1.68	181.622	10.7
Jul	9.52	1.87	196.429	9.7
Aug	10.51	2.61	248.335	9.9
Sep	11.82	3.73	315.567	11.3
Oct	13.20	4.94	374.242	12.4
Nov	14.44	5.90	408.587	13.6
Dec	15.08	6.28	416.446	15.5
Poland				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (℃)
Jan	7.99	0.49	61.327	0.3
Feb	9.75	1.08	110.769	0.1
Mar	11.89	2.38	200.168	1.9
Apr	14.12	3.76	266.289	5.6
May	16.06	5.16	321.295	10.2
Jun	17.10	6.19	361.988	14.2
Jul	16.57	5.23	315.631	17.4
Aug	14.83	4.49	302.765	17.8
Sep	12.68	2.99	235.804	14.3
Oct	10.49	1.52	144.900	10.0
Nov	8.51	0.61	71.680	5.2
Dec	7.45	0.37	49.664	2.0
Portugal				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (℃)
Jan	9.82	2.18	221.996	11.4
Feb	10.77	2.94	272.981	12.3
Mar	11.97	4.33	361.738	13.7
Apr	13.23	5.46	412.698	15.1
May	14.28	6.60	462.185	17.4
Jun	14.80	7.17	484.459	20.2
Jul	14.54	7.43	511.004	22.4
Aug	13.62	6.67	489.721	22.8
Sep	12.41	5.08	409.347	21.7
Oct	11.18	3.57	319.320	18.5
Nov	10.09	2.39	236.868	14.5
Dec	9.55	1.95	204.188	11.8

Romania				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (°C)
Jan	9.32	1.37	146.996	1.2
Feb	10.48	2.24	213.740	1.9
Mar	11.94	3.26	273.032	5.5
Apr	13.47	4.73	351.151	10.3
May	14.76	6.09	412.602	16.0
Jun	15.41	6.86	445.165	20.4
Jul	15.08	6.73	446.286	23.0
Aug	13.95	5.85	419.355	22.8
Sep	12.49	4.47	357.886	18.8
Oct	10.99	2.87	261.146	13.5
Nov	9.66	1.59	164.596	7.4
Dec	8.98	1.14	126.949	2.8

Sweden				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (°C)
Jan	7.03	0.33	46.942	-2.3
Feb	9.26	0.94	101.512	-2.5
Mar	11.86	2.11	177.909	0.0
Apr	14.56	3.63	249.313	4.1
May	17.00	5.25	308.824	9.2
Jun	18.39	5.75	312.670	13.8
Jul	17.68	5.29	299.208	17.3
Aug	15.44	4.18	270.725	16.7
Sep	12.81	2.58	201.405	12.3
Oct	10.17	1.18	116.028	7.3
Nov	7.70	0.44	57.143	2.7
Dec	6.33	0.21	33.175	-0.9

Slovenia				
Month	Daytime (Hours)	Solar radiation (kWh/m^2/d)	Irradiance (W/m^2)	Temperature (°C)
Jan	9.18	1.37	149.237	4.6
Feb	10.41	2.39	229.587	5.1
Mar	11.94	3.58	299.832	8.5
Apr	13.54	5.09	375.923	12.1
May	14.89	6.16	413.700	17.2
Jun	15.58	6.67	428.113	20.7
Jul	15.23	6.70	439.921	23.2
Aug	14.04	5.75	409.544	23.1
Sep	12.51	4.29	342.926	18.8
Oct	10.93	2.68	245.197	14.9

Nov	9.53	1.59	166.842	9.8
Dec	8.82	1.09	123.583	6.3
USA				
Month	Daytime (Hours)	Solar radiation ($kWh/m^2/d$)	Irradiance (W/m^2)	Temperature (℃)
Jan	10.48	2.54	242.366	12.6
Feb	11.15	3.27	293.274	14.4
Mar	12.01	4.20	349.709	17.2
Apr	12.91	5.23	405.112	20.9
May	13.65	5.91	432.967	25.1
Jun	14.02	5.71	407.275	27.6
Jul	13.83	5.69	411.424	28.7
Aug	13.18	5.44	412.747	28.7
Sep	12.32	4.88	396.104	26.8
Oct	11.43	3.89	340.332	22.1
Nov	10.66	3.00	281.426	17.4
Dec	10.28	2.44	237.354	13.3

Table B-2. The amount of electrical energy supply according to the country of the case vessel sailing

Country	AMP	Solar	Total	Power ratio of Solar PV to Total (%)	Ratio of diff. of solar PV generation to assumption (%)
Australia	797014	154850	951864	16.27	25.5
Belgium	852424	99440	951864	10.45	19.4
Bulgaria	834469	117395	951864	12.33	4.9
Brazil	773566	178298	951864	18.73	44.5
Cyprus	783677	168187	951864	17.67	36.3
Germany	863607	88257	951864	9.27	28.5
Denmark	865370	86494	951864	9.09	29.9
Estonia	862585	89279	951864	9.38	27.7
Spain	813672	138192	951864	14.52	12.0
Finland	869556	82308	951864	8.65	33.3
France	854783	97081	951864	10.20	21.3
UK	853159	98705	951864	10.37	20.0
Greece	810223	141641	951864	14.88	14.8
Ireland	872946	78918	951864	8.29	36.1

India	797884	153980	951864	16.18	24.8
Italy	821052	130812	951864	13.74	6.0
Japan	833954	117910	951864	12.39	4.5
Lithuania	853993	97871	951864	10.28	20.7
Latvia	875111	76753	951864	8.06	37.8
Malta	793674	158190	951864	16.62	28.2
Netherlands	857222	94642	951864	9.94	23.3
Norway	865819	86045	951864	9.04	30.3
New Zealand	825184	126680	951864	13.31	2.7
Poland	862244	89620	951864	9.42	27.4
Portugal	806816	145048	951864	15.24	17.5
Romania	828943	122921	951864	12.91	0.4
Sweden	868498	83366	951864	8.76	32.4
Slovenia	828691	123173	951864	12.94	0.2
USA	817979	133885	951864	14.07	8.5
Expectation	828457.5	123406.5	951864	12.96	-

Table B-3. Emissions of the case vessel according to its sailing/bunkering area

Country	<Conventional LCA> Emissions from battery + Solar system for estimated Solar PV generation (kg)				< Live-LCA> Emissions from only battery mode (kg)				< Live-LCA> Emission from battery + Solar system (kg)			
	GWP	AP	EP	POCP	GWP	AP	EP	POCP	GWP	AP	EP	POCP
Australia	820997	3133	283	169	933779	3560	323	190	792261	3025	273	163
Belgium	151604	218	40	20	164672	210	43	20	154142	216	40	20
Bulgaria	611398	2123	130	119	692957	2399	147	133	615371	2136	131	120
Brazil	253504	1451	153	94	281752	1628	172	105	240939	1373	144	89
Cyprus	690101	3945	151	223	783384	4493	170	253	656252	3746	144	213
Germany	458961	610	111	44	517814	661	125	47	475724	624	115	45
Denmark	239420	514	73	36	265570	551	81	38	247242	525	75	37
Estonia	977576	3473	233	210	1113681	3950	265	238	1015215	3605	242	218
Spain	353747	819	92	55	396927	901	103	60	348574	810	91	55
Finland	168173	475	54	39	183710	505	59	41	173347	485	55	40
France	85161	196	27	15	88333	186	28	14	85838	194	27	15
UK	264274	706	56	42	294126	771	61	44	270249	719	57	42

Greece	634594	1302	110	96	719609	1456	124	107	622033	1280	108	94
Ireland	437422	477	56	50	493066	508	61	54	457481	488	58	51
India	886446	10308	472	488	1008976	11803	539	557	856089	9937	455	471
Italy	403455	664	87	51	454039	722	97	55	400419	660	87	51
Japan	531866	590	91	54	601578	638	102	59	534971	592	92	55
Lithuania	194684	616	81	45	214169	667	90	48	198716	626	83	45
Latvia	142491	391	74	33	154202	409	83	34	146918	398	77	34
Malta	536836	791	88	75	607289	869	98	83	516979	769	85	73
Netherlands	440735	371	76	40	496873	386	85	43	453820	375	78	41
Norway	30649	43	4	4	25700	9	2	1	29151	33	3	3
New Zealand	131721	1692	53	23	141828	1904	58	23	131453	1686	53	23
Poland	812713	1675	163	138	924260	1885	185	155	843252	1733	169	143
Portugal	422509	641	104	80	475932	697	116	88	413141	631	101	78
Romania	380258	913	73	60	427387	1009	80	65	380443	913	73	60
Sweden	39348	152	26	19	35695	135	27	18	38163	147	26	18

Slovenia	301555	273	45	26	336960	274	49	26	301622	273	45	26
USA	432451	627	68	47	487354	681	76	51	427789	623	68	47

Table B-4. Functional units of the case vessel according to its sailing/bunkering area

Country	<Conventional LCA> Emissions from battery + Solar system for estimated Solar PV generation (kg)				< Live-LCA> Emissions from only battery mode (kg)				< Live-LCA> Emission from battery + Solar system (kg)			
	GWP	AP	EP	POCP	GWP	AP	EP	POCP	GWP	AP	EP	POCP
Australia	0.8625154	0.00329168	0.00029779	0.00017725	0.9810	0.0037400	0.0003390	0.0002000	0.8323260	0.00317745	0.00028728	0.00017145
Belgium	0.1592704	0.00022891	0.00004181	0.00002119	0.1730	0.0002210	0.0000449	0.0000207	0.1619368	0.00022737	0.00004241	0.00002110
Bulgaria	0.6423162	0.00222985	0.00013677	0.00012503	0.7280	0.0025200	0.0001540	0.0001400	0.6464901	0.00224398	0.00013761	0.00012576
Brazil	0.2663238	0.00152486	0.00016027	0.00009892	0.2960	0.0017100	0.0001810	0.0001100	0.2531237	0.00144251	0.00015105	0.00009398
Cyprus	0.7249997	0.00414463	0.00015853	0.00023469	0.8230	0.0047200	0.0001790	0.0002660	0.6894383	0.00393584	0.00015110	0.00022333
Germany	0.4821713	0.00064059	0.00011675	0.00004652	0.5440	0.0006940	0.0001310	0.0000498	0.4997817	0.00065580	0.00012081	0.00004745
Denmark	0.2515278	0.00054049	0.00007672	0.00003790	0.2790	0.0005790	0.0000850	0.0000399	0.2597451	0.00055201	0.00007919	0.00003850
Estonia	1.0270121	0.00364852	0.00024469	0.00022076	1.1700	0.0041500	0.0002780	0.0002500	1.0665548	0.00378721	0.00025390	0.00022885

Spain	0.3716364	0.00086078	0.00009673	0.00005792	0.4170	0.0009470	0.0001080	0.0000629	0.3662014	0.00085046	0.00009538	0.00005733
Finland	0.1766774	0.00049872	0.00005635	0.00004078	0.1930	0.0005310	0.0000616	0.0000432	0.1821134	0.00050947	0.00005810	0.00004158
France	0.0894681	0.00020628	0.00002798	0.00001571	0.0928	0.0001950	0.0000290	0.0000144	0.0901788	0.00020387	0.00002819	0.00001543
UK	0.2776383	0.00074155	0.00005835	0.00004382	0.3090	0.0008100	0.0000639	0.0000467	0.2839158	0.00075525	0.00005946	0.00004440
Greece	0.6666860	0.00136820	0.00011588	0.00010066	0.7560	0.0015300	0.0001300	0.0001120	0.6534890	0.00134429	0.00011380	0.00009898
Ireland	0.4595421	0.00050133	0.00005861	0.00005226	0.5180	0.0005340	0.0000642	0.0000564	0.4806164	0.00051311	0.00006063	0.00005376
India	0.9312733	0.01082894	0.00049536	0.00051233	1.0600	0.0124000	0.0005660	0.0005850	0.8993817	0.01043971	0.00047785	0.00049433
Italy	0.4238576	0.00069716	0.00009151	0.00005374	0.4770	0.0007590	0.0001020	0.0000581	0.4206686	0.00069345	0.00009088	0.00005348
Japan	0.5587623	0.00061970	0.00009586	0.00005723	0.6320	0.0006700	0.0001070	0.0000621	0.5620243	0.00062194	0.00009636	0.00005744
Lithuania	0.2045287	0.00064668	0.00008516	0.00004678	0.2250	0.0007010	0.0000947	0.0000501	0.2087647	0.00065792	0.00008713	0.00004747
Latvia	0.1496965	0.00041081	0.00007820	0.00003468	0.1620	0.0004300	0.0000867	0.0000362	0.1543478	0.00041807	0.00008141	0.00003526
Malta	0.5639844	0.00083119	0.00009238	0.00007881	0.6380	0.0009130	0.0001030	0.0000869	0.5431223	0.00080813	0.00008939	0.00007653
Netherlands	0.4630235	0.00038992	0.00008020	0.00004226	0.5220	0.0004060	0.0000890	0.0000449	0.4767702	0.00039367	0.00008225	0.00004287
Norway	0.0321989	0.00004519	0.00000423	0.00000372	0.0270	0.0000099	0.0000017	0.0000006	0.0306249	0.00003452	0.00000347	0.00000279
New Zealand	0.1383819	0.00177727	0.00005539	0.00002441	0.1490	0.0020000	0.0000605	0.0000244	0.1381002	0.00177136	0.00005526	0.00002441

Poland	0.8538119	0.00175986	0.00017158	0.00014504	0.9710	0.0019800	0.0001940	0.0001630	0.8858959	0.00182013	0.00017772	0.00014996
Portugal	0.4438757	0.00067366	0.00010892	0.00008395	0.5000	0.0007320	0.0001220	0.0000928	0.4340334	0.00066343	0.00010662	0.00008239
Romania	0.3994877	0.00095913	0.00007628	0.00006297	0.4490	0.0010600	0.0000845	0.0000687	0.3996825	0.00095953	0.00007631	0.00006299
Sweden	0.0413376	0.00016015	0.00002728	0.00001945	0.0375	0.0001420	0.0000282	0.0000187	0.0400924	0.00015426	0.00002758	0.00001921
Slovenia	0.3168042	0.00028722	0.00004738	0.00002729	0.3540	0.0002880	0.0000513	0.0000277	0.3168746	0.00028722	0.00004739	0.00002729
USA	0.4543200	0.00065886	0.00007193	0.00004983	0.5120	0.0007150	0.0000795	0.0000536	0.4494223	0.00065410	0.00007129	0.00004951

C. Appendix for Chapter 7

Table C-1. Functional unit (kg CO_2 eq./kWh) of power source for the ships in terms of production and use based on 27 ferries

No.	Type	Source	Functional unit
1	Type 3	Nuclear	5.680E-03
2	Type 3	Hydro	6.240E-03
3	Type 6-3	Green H2 + Nuclear	6.791E-03
4	Type 6-3	Green H2 + Hydro	7.320E-03
5	Type 4	Solar + Nuclear	7.366E-03
6	Type 4	Solar + Hydro	7.911E-03
7	Type 7-3	Solar + Green H2 + Nuclear	8.477E-03
8	Type 7-3	Solar + Green H2 + Hydro	8.991E-03
9	Type 3	Wind	1.050E-02
10	Type 9-3	Green NH3 + Nuclear	1.078E-02
11	Type 9-3	Green NH3 + Hydro	1.131E-02
12	Type 6-3	Green H2 + Wind	1.135E-02
13	Type 4	Solar + Wind	1.205E-02
14	Type 10-3	Solar + Green NH3 + Nuclear	1.247E-02
15	Type 7-3	Solar + Green H2 + Wind	1.290E-02
16	Type 10-3	Solar + Green NH3 + Hydro	1.298E-02
17	Type 9-3	Green NH3 + Wind	1.534E-02
53	Type 9-2	Green NH3 + Hydro	5.323E-02
54	Type 10-2	Solar + Green NH3 + Nuclear	5.464E-02
55	Type 10-2	Solar + Green NH3 + Hydro	5.490E-02
56	Type 6-1	Green H2 + LNG	5.534E-02
57	Type 9-2	Green NH3 + Wind	5.536E-02
58	Type 10-2	Solar + Green NH3 + Wind	5.692E-02
59	Type 6-1	Green H2 + Oil	6.295E-02
60	Type 6-1	Green H2 + Coal	7.407E-02
61	Type 9-1	Green NH3 + Nuclear	9.512E-02
62	Type 9-1	Green NH3 + Hydro	9.515E-02
63	Type 9-1	Green NH3 + Wind	9.538E-02
64	Type 10-1	Solar + Green NH3 + Nuclear	9.659E-02
65	Type 10-1	Solar + Green NH3 + Hydro	9.661E-02
66	Type 10-1	Solar + Green NH3 + Wind	9.673E-02
67	Type 8	Green NH3	1.002E-01
68	Type 10-1	Solar + Green NH3 + UK elec	1.031E-01
69	Type 6-2	Blue H2 + Nuclear	1.052E-01
105	Type 7-3	Solar + Blue H2 + UK elec	2.252E-01
106	Type 4	Solar + UK elec	2.266E-01
107	Type 6-3	Blue H2 + UK elec	2.297E-01
108	Type 3	UK elec	2.311E-01
109	Type 6-1	Blue H2 + Oil	2.318E-01
110	Type 9-2	Blue NH3 + Nuclear	2.367E-01
111	Type 9-2	Blue NH3 + Hydro	2.370E-01
112	Type 10-2	Solar + Blue NH3 + Nuclear	2.384E-01
113	Type 10-2	Solar + Blue NH3 + Hydro	2.386E-01
114	Type 9-2	Blue NH3 + Wind	2.391E-01
115	Type 10-3	Solar + Blue NH3 + UK elec	2.394E-01
116	Type 10-2	Solar + Blue NH3 + Wind	2.407E-01
117	Type 6-1	Blue H2 + Coal	2.429E-01
118	Type 9-3	Blue NH3 + UK elec	2.439E-01
119	Type 2-3	MGO + UK elec	2.590E-01
120	Type 7-2	Solar + Green H2 + LNG	2.820E-01
121	Type 6-2	Green H2 + LNG	2.956E-01
157	Type 9-2	Green NH3 + Coal	5.061E-01
158	Type 9-2	Blue NH3 + LNG	5.164E-01
159	Type 7-3	Solar + Green H2 + LNG	5.222E-01
160	Type 10-3	Solar + Green NH3 + LNG	5.262E-01
161	Type 7-3	Solar + Blue H2 + LNG	5.319E-01
162	Type 7-2	Solar + Blue H2 + Coal	5.352E-01
163	Type 6-3	Green H2 + LNG	5.359E-01
164	Type 9-3	Green NH3 + LNG	5.399E-01
165	Type 6-3	Blue H2 + LNG	5.456E-01
166	Type 10-3	Solar + Blue NH3 + LNG	5.461E-01
167	Type 4	Solar + LNG	5.513E-01
168	Type 6-2	Blue H2 + Coal	5.584E-01
169	Type 9-3	Blue NH3 + LNG	5.597E-01
170	Type 3	Natural gas (LNG)	5.650E-01
171	Type 10-2	Solar + Blue NH3 + Oil	5.693E-01
172	Type 2-3	MGO + LNG	5.748E-01
173	Type 9-2	Blue NH3 + Oil	5.869E-01

18	Type 6-2	Green H2 + Nuclear	1.597E-02	70	Type 6-2	Blue H2 + Hydro	1.055E-01	122	Type 10-2	Solar + Green NH3 + LNG	3.189E-01	174	Type 7-3	Solar + Green H2 + Oil	6.518E-01
19	Type 6-2	Green H2 + Hydro	1.625E-02	71	Type 7-2	Solar + Blue H2 + Nuclear	1.069E-01	123	Type 9-2	Green NH3 + LNG	3.326E-01	175	Type 10-3	Solar + Green NH3 + Oil	6.558E-01
20	Type 6-3	Blue H2 + Nuclear	1.643E-02	72	Type 7-2	Solar + Blue H2 + Hydro	1.072E-01	124	Type 10-2	Solar + Blue NH3 + UK elec	3.449E-01	176	Type 2-2	MGO + LNG	6.558E-01
21	Type 10-3	Solar + Green NH3 + Wind	1.690E-02	73	Type 9-1	Green NH3 + UK elec	1.073E-01	125	Type 7-2	Solar + Green H2 + Oil	3.486E-01	177	Type 7-3	Solar + Blue H2 + Oil	6.614E-01
22	Type 6-3	Blue H2 + Hydro	1.696E-02	74	Type 6-2	Blue H2 + Wind	1.076E-01	126	Type 9-2	Blue NH3 + UK elec	3.494E-01	178	Type 10-2	Solar + Blue NH3 + Coal	6.667E-01
23	Type 7-2	Solar + Green H2 + Nuclear	1.765E-02	75	Type 7-2	Solar + Blue H2 + Wind	1.092E-01	127	Type 6-2	Green H2 + Oil	3.661E-01	179	Type 6-3	Green H2 + Oil	6.693E-01
24	Type 7-2	Solar + Green H2 + Hydro	1.792E-02	76	Type 10-1	Solar + Green NH3 + LNG	1.127E-01	128	Type 7-2	Solar + Blue H2 + LNG	3.712E-01	180	Type 9-3	Green NH3 + Oil	6.733E-01
25	Type 7-3	Solar + Blue H2 + Nuclear	1.811E-02	77	Type 10-1	Solar + Green NH3 + Oil	1.168E-01	129	Type 2-2	MGO + Nuclear	3.762E-01	181	Type 10-3	Solar + Blue NH3 + Oil	6.756E-01
26	Type 6-2	Green H2 + Wind	1.838E-02	78	Type 10-1	Solar + Green NH3 + Coal	1.227E-01	130	Type 2-2	MGO + Hydro	3.765E-01	182	Type 6-3	Blue H2 + Oil	6.789E-01
27	Type 7-3	Solar + Blue H2 + Hydro	1.863E-02	79	Type 7-2	Solar + Green H2 + UK elec	1.242E-01	131	Type 2-2	MGO + Wind	3.786E-01	183	Type 4	Solar + Oil	6.885E-01
28	Type 7-2	Solar + Green H2 + Wind	1.993E-02	80	Type 9-1	Green NH3 + LNG	1.253E-01	132	Type 6-2	Blue H2 + LNG	3.849E-01	184	Type 9-2	Blue NH3 + Coal	6.899E-01
29	Type 6-3	Blue H2 + Wind	2.099E-02	81	Type 6-2	Green H2 + UK elec	1.287E-01	133	Type 10-2	Solar + Green NH3 + Oil	3.856E-01	185	Type 9-3	Blue NH3 + Oil	6.931E-01
30	Type 7-3	Solar + Blue H2 + Wind	2.254E-02	82	Type 9-1	Green NH3 + Oil	1.329E-01	134	Type 9-2	Green NH3 + Oil	4.031E-01	186	Type 3	Oil	7.060E-01
31	Type 6-1	Green H2 + Nuclear	2.514E-02	83	Type 9-1	Green NH3 + Coal	1.441E-01	135	Type 7-2	Solar + Blue H2 + Oil	4.378E-01	187	Type 2-1	MGO + Nuclear	7.067E-01
32	Type 6-1	Green H2 + Hydro	2.517E-02	84	Type 10-2	Solar + Green NH3 + UK elec	1.612E-01	136	Type 9-1	Blue NH3 + Nuclear	4.428E-01	188	Type 2-1	MGO + Hydro	7.067E-01
33	Type 6-1	Green H2 + Wind	2.540E-02	85	Type 9-2	Green NH3 + UK elec	1.657E-01	137	Type 9-1	Blue NH3 + Hydro	4.428E-01	189	Type 2-1	MGO + Wind	7.069E-01
34	Type 5	Green H2	2.625E-02	86	Type 6-1	Blue H2 + Nuclear	1.940E-01	138	Type 9-1	Blue NH3 + Wind	4.430E-01	190	Type 2-3	MGO + Oil	7.082E-01
35	Type 7-1	Solar + Green H2 + Nuclear	2.678E-02	87	Type 6-1	Blue H2 + Hydro	1.940E-01	139	Type 10-1	Solar + Blue NH3 + Nuclear	4.434E-01	191	Type 2-1	MGO + UK elec	7.189E-01
36	Type 7-1	Solar + Green H2 + Hydro	2.680E-02	88	Type 6-1	Blue H2 + Wind	1.943E-01	140	Type 10-1	Solar + Blue NH3 + Hydro	4.434E-01	192	Type 2-2	MGO + Oil	7.263E-01
37	Type 7-1	Solar + Green H2 + Wind	2.692E-02	89	Type 7-1	Solar + Blue H2 + Nuclear	1.952E-01	141	Type 10-1	Solar + Blue NH3 + Wind	4.436E-01	193	Type 2-1	MGO + LNG	7.369E-01
38	Type 9-3	Blue NH3 + Nuclear	3.062E-02	90	Type 7-1	Solar + Blue H2 + Hydro	1.953E-01	142	Type 7-2	Solar + Green H2 + Coal	4.459E-01	194	Type 2-1	MGO + Oil	7.445E-01
39	Type 9-3	Blue NH3 + Hydro	3.115E-02	91	Type 7-1	Solar + Blue H2 + Wind	1.954E-01	143	Type 10-1	Solar + Blue NH3 + UK elec	4.499E-01	195	Type 1	MGO	7.467E-01
40	Type 10-3	Solar + Blue NH3 + Nuclear	3.231E-02	92	Type 7-1	Solar + Blue H2 + UK elec	2.017E-01	144	Type 9-1	Blue NH3 + UK elec	4.549E-01	196	Type 2-1	MGO + Coal	7.556E-01

41	Type 10-3	Solar + Blue NH3 + Hydro	3.282E-02	93	Type 5	Blue H2	2.048E-01	145	Type 6-2	Blue H2 + Oil	4.554E-01	197	Type 2-2	MGO + Coal	8.293E-01
42	Type 7-1	Solar + Green H2 + UK elec	3.327E-02	94	Type 6-1	Blue H2 + UK elec	2.062E-01	146	Type 10-1	Solar + Blue NH3 + LNG	4.595E-01	198	Type 7-3	Solar + Green H2 + Coal	8.410E-01
43	Type 9-3	Blue NH3 + Wind	3.518E-02	95	Type 7-1	Solar + Blue H2 + LNG	2.113E-01	147	Type 10-1	Solar + Blue NH3 + Oil	4.636E-01	199	Type 10-3	Solar + Green NH3 + Coal	8.450E-01
44	Type 10-3	Solar + Blue NH3 + Wind	3.674E-02	96	Type 7-2	Solar + Blue H2 + UK elec	2.134E-01	148	Type 8	Blue NH3	4.677E-01	200	Type 7-3	Solar + Blue H2 + Coal	8.506E-01
45	Type 6-1	Green H2 + UK elec	3.731E-02	97	Type 7-1	Solar + Blue H2 + Oil	2.154E-01	149	Type 6-2	Green H2 + Coal	4.691E-01	201	Type 6-3	Green H2 + Coal	8.642E-01
46	Type 7-1	Solar + Green H2 + LNG	4.288E-02	98	Type 7-3	Solar + Green H2 + UK elec	2.156E-01	150	Type 10-1	Solar + Blue NH3 + Coal	4.695E-01	202	Type 10-3	Solar + Blue NH3 + Coal	8.648E-01
47	Type 2-3	MGO + Nuclear	4.569E-02	99	Type 6-2	Blue H2 + UK elec	2.179E-01	151	Type 9-1	Blue NH3 + LNG	4.730E-01	203	Type 9-3	Green NH3 + Coal	8.682E-01
48	Type 2-3	MGO + Hydro	4.622E-02	100	Type 10-3	Solar + Green NH3 + UK elec	2.196E-01	152	Type 9-1	Blue NH3 + Oil	4.806E-01	204	Type 6-3	Blue H2 + Coal	8.738E-01
49	Type 7-1	Solar + Green H2 + Oil	4.694E-02	101	Type 6-3	Green H2 + UK elec	2.201E-01	153	Type 10-2	Solar + Green NH3 + Coal	4.829E-01	205	Type 9-3	Blue NH3 + Coal	8.880E-01
50	Type 2-3	MGO + Wind	5.025E-02	102	Type 7-1	Solar + Blue H2 + Coal	2.213E-01	154	Type 2-2	MGO + UK elec	4.889E-01	206	Type 4	Solar + Coal	8.888E-01
51	Type 7-1	Solar + Green H2 + Coal	5.288E-02	103	Type 9-3	Green NH3 + UK elec	2.241E-01	155	Type 9-1	Blue NH3 + Coal	4.917E-01	207	Type 2-3	MGO + Coal	9.031E-01
52	Type 9-2	Green NH3 + Nuclear	5.295E-02	104	Type 6-1	Blue H2 + LNG	2.242E-01	156	Type 10-2	Solar + Blue NH3 + LNG	5.027E-01	208	Type 3	Coal	9.120E-01

Table C-2. GWP Functional unit (kg CO_2 eq./kWh) in terms of fuel lifecycle based on 27 ferries operating in Scotland

Type	**Source**	**Functional unit**	**Type**	**Source**	**Functional unit**	**Type**	**Source**	**Functional unit**	**Type**	**Source**	**Functional unit**
Type 3	Nuclear	5.680E-03	Type 6-2	Blue H2 + Wind	1.920E-01	Type 7-2	Solar + Green H2 + LNG	3.661E-01	Type 2-2 (day)	MGO + LNG	6.610E-01
Type 3	Hydro	6.240E-03	Type 7-1	Solar + Green H2 + UK elec	1.922E-01	Type 7-1	Solar + Blue H2 + LNG	3.706E-01	Type 9-1	Blue NH3 + UK elec	6.659E-01
Type 4	Solar + Nuclear	7.366E-03	Type 7-2	Solar + Blue H2 + Wind	1.935E-01	Type 5	Blue H2	3.734E-01	Type 10-3	Solar + Green NH3 + Oil	6.668E-01
Type 4	Solar + Hydro	7.911E-03	Type 5	Green H2	1.946E-01	Type 7-1	Solar + Blue H2 + Oil	3.746E-01	Type 10-1	Solar + Blue NH3 + LNG	6.699E-01

Type 3	Wind	1.050E-02	Type 6-1	Green H2 + UK elec	1.966E-01	Type 2-2 (week)	MGO + Nuclear	3.774E-01	Type 7-3	Solar + Blue H2 + Oil	6.705E-01
Type 4	Solar + Wind	1.205E-02	Type 7-1	Solar + Green H2 + LNG	2.018E-01	Type 2-2 (week)	MGO + Hydro	3.777E-01	Type 10-1	Solar + Blue NH3 + Oil	6.740E-01
Type 6-3	Green H2 + Nuclear	1.588E-02	Type 7-1	Solar + Green H2 + Oil	2.058E-01	Type 6-2	Green H2 + LNG	3.798E-01	Type 6-3	Green H2 + Oil	6.784E-01
Type 6-3	Green H2 + Hydro	1.641E-02	Type 7-2	Solar + Green H2 + UK elec	2.084E-01	Type 2-2 (week)	MGO + Wind	3.799E-01	Type 10-1	Solar + Blue NH3 + Coal	6.799E-01
Type 7-3	Solar + Green H2 + Nuclear	1.757E-02	Type 7-1	Solar + Green H2 + Coal	2.118E-01	Type 7-1	Solar + Blue H2 + Coal	3.806E-01	Type 10-2	Solar + Blue NH3 + Oil	6.808E-01
Type 7-3	Solar + Green H2 + Hydro	1.808E-02	Type 6-2	Green H2 + UK elec	2.129E-01	Type 2-2 (day)	MGO + Nuclear	3.814E-01	Type 9-1	Blue NH3 + LNG	6.839E-01
Type 6-3	Green H2 + Wind	2.044E-02	Type 6-1	Green H2 + LNG	2.146E-01	Type 2-2 (day)	MGO + Hydro	3.816E-01	Type 9-3	Green NH3 + Oil	6.843E-01
Type 9-3	Green NH3 + Nuclear	2.182E-02	Type 6-1	Green H2 + Oil	2.222E-01	Type 2-2 (day)	MGO + Wind	3.838E-01	Type 10-3	Solar + Blue NH3 + Oil	6.876E-01
Type 7-3	Solar + Green H2 + Wind	2.199E-02	Type 7-3	Solar + Green H2 + UK elec	2.246E-01	Type 6-1	Blue H2 + LNG	3.838E-01	Type 6-3	Blue H2 + Oil	6.880E-01
Type 9-3	Green NH3 + Hydro	2.235E-02	Type 4	Solar + UK elec	2.266E-01	Type 6-1	Blue H2 + Oil	3.914E-01	Type 4	Solar + Oil	6.885E-01
Type 10-3	Solar + Green NH3 + Nuclear	2.350E-02	Type 6-3	Green H2 + UK elec	2.291E-01	Type 6-1	Blue H2 + Coal	4.025E-01	Type 8	Blue NH3	6.907E-01
Type 10-3	Solar + Green NH3 + Hydro	2.402E-02	Type 10-3	Solar + Green NH3 + UK elec	2.306E-01	Type 10-2	Solar + Green NH3 + LNG	4.205E-01	Type 9-1	Blue NH3 + Oil	6.915E-01
Type 6-3	Blue H2 + Nuclear	2.553E-02	Type 3	UK elec	2.311E-01	Type 7-2	Solar + Green H2 + Oil	4.328E-01	Type 9-2	Blue NH3 + Oil	6.983E-01
Type 6-3	Blue H2 + Hydro	2.606E-02	Type 6-1	Green H2 + Coal	2.333E-01	Type 9-2	Green NH3 + LNG	4.342E-01	Type 9-1	Blue NH3 + Coal	7.026E-01
Type 9-3	Green NH3 + Wind	2.638E-02	Type 7-3	Solar + Blue H2 + UK elec	2.343E-01	Type 6-2	Green H2 + Oil	4.503E-01	Type 9-3	Blue NH3 + Oil	7.052E-01
Type 7-3	Solar + Blue H2 + Nuclear	2.722E-02	Type 9-3	Green NH3 + UK elec	2.351E-01	Type 7-2	Solar + Blue H2 + LNG	4.556E-01	Type 3	Oil	7.060E-01
Type 7-3	Solar + Blue H2 + Hydro	2.773E-02	Type 6-3	Blue H2 + UK elec	2.388E-01	Type 10-2	Solar + Blue NH3 + UK elec	4.564E-01	Type 2-1 (week)	MGO + Nuclear	7.084E-01
Type 10-3	Solar + Green NH3 + Wind	2.793E-02	Type 10-3	Solar + Blue NH3 + UK elec	2.514E-01	Type 9-2	Blue NH3 + UK elec	4.609E-01	Type 2-1 (week)	MGO + Hydro	7.084E-01
Type 6-3	Blue H2 + Wind	3.009E-02	Type 9-3	Blue NH3 + UK elec	2.559E-01	Type 6-2	Blue H2 + LNG	4.692E-01	Type 2-1 (week)	MGO + Wind	7.087E-01
Type 7-3	Solar + Blue H2 + Wind	3.165E-02	Type 2-3 (week)	MGO + UK elec	2.597E-01	Type 10-2	Solar + Green NH3 + Oil	4.872E-01	Type 2-3 (week)	MGO + Oil	7.089E-01
Type 9-3	Blue NH3 + Nuclear	4.264E-02	Type 10-2	Solar + Green NH3 + UK elec	2.628E-01	Type 2-2 (week)	MGO + UK elec	4.902E-01	Type 2-1 (day)	MGO + Nuclear	7.124E-01
Type 9-3	Blue NH3 + Hydro	4.317E-02	Type 2-3 (day)	MGO + UK elec	2.639E-01	Type 2-2 (day)	MGO + UK elec	4.941E-01	Type 2-1 (day)	MGO + Hydro	7.124E-01
Type 10-3	Solar + Blue NH3 + Nuclear	4.433E-02	Type 9-2	Green NH3 + UK elec	2.673E-01	Type 9-2	Green NH3 + Oil	5.047E-01	Type 2-1 (day)	MGO + Wind	7.126E-01

Type 10-3	Solar + Blue NH3 + Hydro	4.484E-02
Type 2-3 (week)	MGO + Nuclear	4.639E-02
Type 2-3 (week)	MGO + Hydro	4.692E-02
Type 9-3	Blue NH3 + Wind	4.720E-02
Type 10-3	Solar + Blue NH3 + Wind	4.876E-02
Type 2-3 (day)	MGO + Nuclear	5.064E-02
Type 2-3 (week)	MGO + Wind	5.095E-02
Type 2-3 (day)	MGO + Hydro	5.117E-02
Type 2-3 (day)	MGO + Wind	5.520E-02
Type 6-2	Green H2 + Nuclear	1.001E-01
Type 6-2	Green H2 + Hydro	1.004E-01
Type 7-2	Solar + Green H2 + Nuclear	1.018E-01
Type 7-2	Solar + Green H2 + Hydro	1.021E-01
Type 6-2	Green H2 + Wind	1.026E-01
Type 7-2	Solar + Green H2 + Wind	1.041E-01
Type 9-2	Green NH3 + Nuclear	1.546E-01
Type 9-2	Green NH3 + Hydro	1.548E-01
Type 10-2	Solar + Green NH3 + Nuclear	1.562E-01
Type 10-2	Solar + Green NH3 + Hydro	1.565E-01
Type 9-2	Green NH3 + Wind	1.570E-01
Type 10-2	Solar + Green NH3 + Wind	1.585E-01
Type 6-1	Green H2 + Nuclear	1.844E-01
Type 6-1	Green H2 + Hydro	1.844E-01
Type 9-1	Green NH3 + Nuclear	2.873E-01
Type 9-1	Green NH3 + Hydro	2.873E-01
Type 9-1	Green NH3 + Wind	2.876E-01
Type 10-1	Solar + Green NH3 + Nuclear	2.883E-01
Type 10-1	Solar + Green NH3 + Hydro	2.883E-01
Type 10-1	Solar + Green NH3 + Wind	2.884E-01
Type 10-1	Solar + Green NH3 + UK elec	2.948E-01
Type 7-2	Solar + Blue H2 + UK elec	2.978E-01
Type 9-1	Green NH3 + UK elec	2.995E-01
Type 6-2	Blue H2 + UK elec	3.023E-01
Type 8	Green NH3	3.034E-01
Type 10-1	Solar + Green NH3 + LNG	3.044E-01
Type 10-1	Solar + Green NH3 + Oil	3.085E-01
Type 10-1	Solar + Green NH3 + Coal	3.144E-01
Type 9-1	Green NH3 + LNG	3.175E-01
Type 9-1	Green NH3 + Oil	3.251E-01
Type 9-1	Green NH3 + Coal	3.362E-01
Type 9-2	Blue NH3 + Nuclear	3.482E-01
Type 9-2	Blue NH3 + Hydro	3.484E-01
Type 10-2	Solar + Blue NH3 + Nuclear	3.499E-01
Type 10-2	Solar + Blue NH3 + Hydro	3.501E-01
Type 9-2	Blue NH3 + Wind	3.506E-01
Type 10-2	Solar + Blue NH3 + Wind	3.521E-01
Type 7-2	Solar + Blue H2 + Oil	5.222E-01
Type 7-2	Solar + Green H2 + Coal	5.301E-01
Type 7-3	Solar + Green H2 + LNG	5.313E-01
Type 10-3	Solar + Green NH3 + LNG	5.373E-01
Type 6-2	Blue H2 + Oil	5.397E-01
Type 7-3	Solar + Blue H2 + LNG	5.410E-01
Type 6-3	Green H2 + LNG	5.450E-01
Type 9-3	Green NH3 + LNG	5.509E-01
Type 4	Solar + LNG	5.513E-01
Type 6-2	Green H2 + Coal	5.533E-01
Type 6-3	Blue H2 + LNG	5.547E-01
Type 10-3	Solar + Blue NH3 + LNG	5.581E-01
Type 3	Natural gas (LNG)	5.650E-01
Type 9-3	Blue NH3 + LNG	5.718E-01
Type 2-3 (week)	MGO + LNG	5.755E-01
Type 2-3 (day)	MGO + LNG	5.798E-01
Type 10-2	Solar + Green NH3 + Coal	5.845E-01
Type 9-2	Green NH3 + Coal	6.077E-01
Type 10-2	Solar + Blue NH3 + LNG	6.142E-01
Type 7-2	Solar + Blue H2 + Coal	6.195E-01
Type 9-2	Blue NH3 + LNG	6.278E-01
Type 6-2	Blue H2 + Coal	6.427E-01
Type 9-1	Blue NH3 + Nuclear	6.537E-01
Type 2-3 (day)	MGO + Oil	7.131E-01
Type 2-1 (week)	MGO + UK elec	7.206E-01
Type 2-1 (day)	MGO + UK elec	7.245E-01
Type 2-2 (week)	MGO + Oil	7.276E-01
Type 2-2 (day)	MGO + Oil	7.315E-01
Type 2-1 (week)	MGO + LNG	7.386E-01
Type 2-1 (day)	MGO + LNG	7.426E-01
Type 2-1 (week)	MGO + Oil	7.462E-01
Type 1 (week)	MGO	7.485E-01
Type 2-1 (day)	MGO + Oil	7.502E-01
Type 1 (day)	MGO	7.524E-01
Type 2-1 (week)	MGO + Coal	7.573E-01
Type 2-1 (day)	MGO + Coal	7.613E-01
Type 10-2	Solar + Blue NH3 + Coal	7.781E-01
Type 9-2	Blue NH3 + Coal	8.013E-01
Type 2-2 (week)	MGO + Coal	8.306E-01
Type 2-2 (day)	MGO + Coal	8.345E-01
Type 7-3	Solar + Green H2 + Coal	8.501E-01
Type 10-3	Solar + Green NH3 + Coal	8.560E-01
Type 7-3	Solar + Blue H2 + Coal	8.597E-01
Type 6-3	Green H2 + Coal	8.733E-01
Type 10-3	Solar + Blue NH3 + Coal	8.768E-01
Type 9-3	Green NH3 + Coal	8.792E-01

Type 6-1	Green H2 + Wind	1.847E-01	Type 6-1	Blue H2 + Nuclear	3.536E-01	Type 9-1	Blue NH3 + Hydro	6.537E-01	Type 6-3	Blue H2 + Coal	8.829E-01
Type 7-1	Solar + Green H2 + Nuclear	1.857E-01	Type 6-1	Blue H2 + Hydro	3.536E-01	Type 10-1	Solar + Blue NH3 + Nuclear	6.538E-01	Type 4	Solar + Coal	8.888E-01
Type 7-1	Solar + Green H2 + Hydro	1.857E-01	Type 6-1	Blue H2 + Wind	3.539E-01	Type 10-1	Solar + Blue NH3 + Hydro	6.539E-01	Type 9-3	Blue NH3 + Coal	9.000E-01
Type 7-1	Solar + Green H2 + Wind	1.858E-01	Type 7-1	Solar + Blue H2 + Nuclear	3.545E-01	Type 9-1	Blue NH3 + Wind	6.540E-01	Type 2-3 (week)	MGO + Coal	9.038E-01
Type 6-2	Blue H2 + Nuclear	1.896E-01	Type 7-1	Solar + Blue H2 + Hydro	3.545E-01	Type 10-1	Solar + Blue NH3 + Wind	6.540E-01	Type 2-3 (day)	MGO + Coal	9.080E-01
Type 6-2	Blue H2 + Hydro	1.898E-01	Type 7-1	Solar + Blue H2 + Wind	3.546E-01	Type 2-2 (week)	MGO + LNG	6.571E-01	Type 3	Coal	9.120E-01
Type 7-2	Solar + Blue H2 + Nuclear	1.912E-01	Type 7-1	Solar + Blue H2 + UK elec	3.609E-01	Type 10-1	Solar + Blue NH3 + UK elec	6.603E-01			
Type 7-2	Solar + Blue H2 + Hydro	1.915E-01	Type 6-1	Blue H2 + UK elec	3.658E-01	Type 7-3	Solar + Green H2 + Oil	6.609E-01			