University of Strathclyde

Department of Naval Architecture, Ocean, and Marine Engineering

PARAMETRIC TREND LIFE CYCLE ASSESSMENT FOR CLEANER SHIPPING

by

Hayoung Jang

A thesis presented in fulfilment of the requirements for the 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, Gwangmun Jang, Jumduk Chae & Byoungjo Jang

ABSTRACT

As environmental awareness increases along with the climate crisis, efforts for more eco-friendly shipping are being emphasized. International maritime regulations have begun to regulate the emissions of ships more stringently through MARPOL, and in response, so-called eco-friendly marine fuels and systems such as LNG, hydrogen fuel cells and scrubber systems have begun to be introduced.

However, approaches for measuring environmental friendliness and tightening regulations of the current shipping industry, are not designed to be applicable to the upcoming eco-friendly marine systems and fuels, but also have limitations in focusing only on the fuel consumption phase. In addition, it is impossible to consistently measure the eco-friendliness of ships in all fleets from an integrated point of view.

In this context, generally measuring the eco-friendliness of alternative marine fuels and systems could exacerbate such a fundamental issue for serious climate crisis and marine environmental problems.

To overcome those identified limitations, parametric trend life cycle assessment (PT-LCA) was developed and applied to representative marine alternative fuels and systems which are SOx scrubber systems, LNG fueled ships, and hydrogen fuel cells.

As a result, it was found that ship age and power were closely related key parameters and the proposed LCA-based methodology can evaluate the different emission levels of fuels and systems applied to various ships by reflecting LCA perspective, as well as obtain the general trends of emission levels over ship parameters expressed as simple equations.

In addition, the proposed approaches taken to develop those frameworks are strongly believed to offer a meaningful insight into future regulatory and decision-making frameworks. Thus, the novelty of this project can be placed on the provision of an insight into the optimal selection of alternative fuels and systems depending on ship characteristics.

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PUBLICATIONS

Conferences

- Introduction of Parametric Trend Life Cycle Assessment for SOx reduction scrubber systems (WSOS) 2020, Glasgow, UK.
- Life Cycle Assessment for marine SOx reduction scrubber systems (YRS) 2019, Greece.

Journals

- **Jang, H**., Jeong, B., Zhou, P., Ha, S., & Nam, D. (2021). Demystifying the lifecycle environmental benefits and harms of LNG as marine fuel. Applied Energy, 292, 116869. https://doi.org/10.1016/j.apenergy.2021.116869
- **Jang, H**., Jeong, B., Zhou, P., Ha, S., Nam, D., Kim, J., & Lee, J. U. (2020). Development of Parametric Trend Life Cycle Assessment for Marine SOx Reduction Scrubber Systems. Journal of Cleaner Production, 122821. https://doi.org/10.1016/j.jclepro.2020.122821

Additional Journals done during Ph.D. period

- **Jang H**., Jeong B., Zhou P., Ha S., Nam D., Rashedi A., (2022), Parametric trend life cycle assessment for Hydrogen fuel cell towards cleaner shipping submitted to Journal of Cleaner production ***(Under 2nd review)***
- Chalaris I., **Jang H**., Jeong, B., **(**2022), Application of Parametric trend life cycle assessment for investigating the carbon footprint of ammonia as marine fuel (***Under 2nd review***)

REPRESENTATIVE PROJECTS

- **H2020 [Industrial project]**

  Ship Lifecycle Software Solutions (SHIPLYS) H2020 SC3 (CoI), European Commission - Horizon 2020 Sep. 2016 to Aug. 2019
  The project aim is to develop ship lifecycle assessment software for EU SME shipyards (To partly collect related databases, not directly related to my PhD work).

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GLOSSARY

AE	Auxiliary Engine
AP	Acidification Potential
CO_2 Equivalence.	Expression of the GWP in terms of CO_2 for the following three components CO_2, CH_4, N_2O, based on IPCC weighting factors
Cu-Cl	Copper-Chlorine
DWT	Dead Weight Tonnage
ECA	Emission Control Areas
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EGCS	Exhaust Gas Cleaning System
EGR	Exhaust Gas Recirculation
EP	Eutrophication Potential
GHG	Greenhouse Gases
GRE	Glass Reinforced Epoxy
GWP	Global Warming Potential
HCl	Hydrogen Chloride
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LBSI Engines	Lean Burn Spark-ignited Engines
LCA	Life Cycle Assessment
LNG	Liquid Natural Gas
LSD Engines	Low-speed Diesel Cycle Engines
LS-HPDF Engines	Low-speed High-pressure Dual-fuel Engines
LS-LPDF Engines	Low-speed Low-pressure Dual-fuel Engines
m/m	mass by mass
MARPOL	International Convention for the Prevention of Pollution from Ships
MCDA	Multiple-Criteria Decision making Analysis
MCFC	Molten Carbonate Fuel Cell
ME	Main Engine
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MS-LPDF Engines	Medium-speed Low-pressure Dual-fuel Engines
NaOH	Sodium Hydroxide
NG	Natural Gas
NOx	Nitrogen Oxides
PEMFC	Proton Exchange Membrane Fuel Cell
PT-LCA	Parametric Trend LCA
PM	Particulate Matter
PO_4 Equivalence.	Expression of the EP in terms of PO_4 for the following three components NO_3, NH_3, PO_4 based on IPCC weighting factors
Ro-Ro vessel	Roll-on/roll-off vessel designed to carry wheeled cargo
SCR System	Selective Catalytic Reduction System
SEEMP	Ship Energy Efficiency Management Plan
SFC	Specific Fuel Consumptions
SFOC	Specific Fuel Oil Consumptions
SNG	Synthetic Natural Gas
SOFC	Solid Oxide Fuel Cell

SO_2 Equivalence.	Expression of the AP in terms of SO_2 for the following three components SO_2, NH_3 based on IPCC weighting factors
SOx	Sulphur Oxides
TTW	Tank-To-Wake
ULSFO	Ultra-Low Sulphur Fuel Oil
WTT	Well-To-Tank
WTW	Well-To-Wake
WWTP	Wastewater Treatment Plant

1. INTRODUCTION

1.1. Overview

Key environmental issues such as global warming, acidification and eutrophication from shipping, which account for more than 80% of world trade, has been considered serious threats to green shipping (Cepeda, Pereira, Kahn, & Caprace, 2019). The shipping industry, which emits more than approximately 1 billion tonnes of greenhouse gas (GHG) per year, is projected to steadily increase GHG by 90% to 130% by 2050 compared to 2008 (IMO, 2020). In addition, nearly 70% of ship emissions, such as sulphur oxides (SOx) and nitrogen oxides (NOx), occur within 400 km above the ground, with significant negative impacts (Eyring et al., 2010; Russo, Leitão, Gama, Ferreira, & Monteiro, 2018). The global warming effect has caused drastic changes to entire ecosystems because of sea level rise and frequent disasters such as heatwaves and droughts (Zandalinas, Fritschi, & Mittler, 2021). Also, air pollution has a very significant impact on human health such as mortality, respiratory disease (Liao, Du, & Chen, 2021). Since this is directly related to the continued prosperity and survival of humankind, it has been considered very urgent and important issue for shipping to become more eco-friendly as part of mitigating the global warming and air pollution.

1.2. Countermeasures

To mitigate the impacts of global warming and air pollution from shipping, the International Maritime Organization (IMO) and local governments have developed a series of stringent environmental rules and guidelines associated with CO_2, CO, CH_4, HCl, NOx, SOx and NMVOC over the past few decades (IMO, 2014, 2018). In particular, the marine environment protection committee (MEPC) has established an ambitious goal by adopting a new resolution to curtail GHG emission by at least 50% by 2050 compared to 2008 as shown in Figure 1-1 (IMO, 2014). Following this trend, the IMO adopted resolution MEPC.203 (62), a mandatory measure to improve energy efficiency in international shipping, at the 62nd MEPC in July 2011 to reduce GHG emissions introducing a new regulation on energy efficiency of ships in Chapter 4 of Annex VI of International Convention for the Prevention of Pollution from Ships (MARPOL). Therefore, a new ship must be built within the allowable range of the energy efficiency design index (EEDI) stipulated as a technical measure, and the ship energy efficiency management plan (SEEMP) as an operational measure was forced to be kept by ships engaged in international voyages. These measures came into effect on 1st January 2013 and began to apply to all ships of 400 gross tonnage or more. In addition, at the 76th MEPC meeting, as the amendments to the convention on the prevention of marine pollution for GHG emission regulation applied to existing ships on international voyages were adopted, the technical measure of the existing vessel energy efficiency index (EEXI) and the operational measure of the carbon intensity index (CII) was introduced. The amendment of MARPOL Annex VI to reduce the carbon intensity of existing ships was adopted as Resolution MEPC.328(76), and the amendment is scheduled to take effect on 1st January 2022.

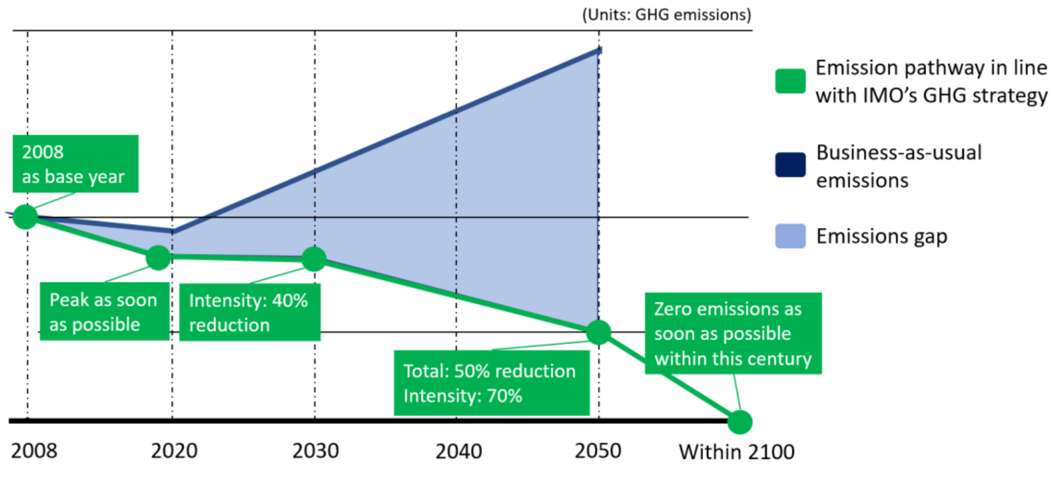

Figure 1-1. IMO strategy for major reduction in GHG emissions from shipping (DNV, 2019).

In the meantime, since the emissions of SOx and NOx from ship exhaust gas also have an adverse effect on the marine environment, the IMO has implemented a series of strict regulations limiting those local emissions through the MARPOL Annex VI (El-Houjeiri, Monfort, Bouchard, & Przesmitzki, 2019). It introduces progressive limitations of sulphur content levels in fuels as low as 0.5 % m/m (mass by mass) globally since 1st January 2020. The restriction level is more severely applied in emission control areas (ECA) where the sulphur contents in fuels should not exceed 0.1 % m/m since 2015 (IMO, 2018). As such, SOx emissions are limited by the sulphur content in the fuel, while NOx emission regulations are limited by the engine speed of used and new marine diesel vessels (Van, Ramirez, Rainey, Ristovski, & Brown, 2019).

To meet these increasingly stringent regulations and address the current serious environmental crisis, various alternative fuels and emission reduction technologies have been proposed. Until recently, heavy fuel oil (HFO) as well as low sulphur fuel oil (LSFO) and marine gas oil (MGO) was the dominant marine fuel for ships. However, as shown in Figure 1-2, the use of those fuels is gradually decreasing, whereas alternative fuels and systems such as liquefied natural gas (LNG), hydrogen, ammonia, and aftertreatment technologies such as scrubber systems and selective catalytic reduction (SCR) are highly expected to be further proposed and commercialized by 2050.

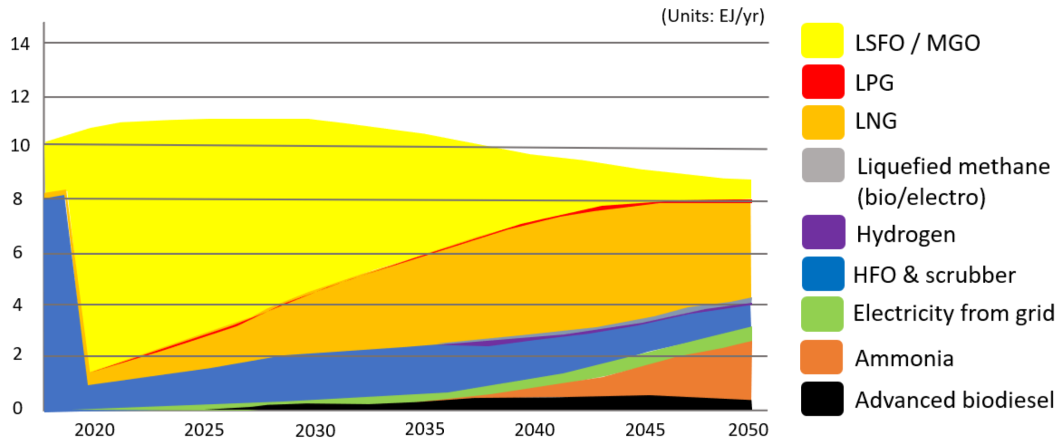

Figure 1-2. Energy use and projected fuel mix 2018-2050 for the simulated IMO ambitious pathway with focus on design requirements (DNV, 2019).

1.3. Motivations

In order to cope with serious environmental issues including global warming, environmental regulations on shipping are getting stringent, and the attention of alternative fuels and systems is increasing.

Nevertheless, since there are still many uncertainties about whether the ambitious goal set in shipping can be achieved, it has been inevitably required an appropriate environmental assessment tool to measure if future marine fuels and systems are on the right track based on the following motivations in this section.

- The current regulatory method to reduce the amount of CO_2 generated by ships to alleviate global warming by increasing ship efficiency through EEDI, EEOI, and SEEMP does not include reduction of other greenhouse gases such as methane and N_2O emissions. Accordingly, environmental assessments and related regulation are inevitably incomplete because only one factor among the numerous factors affecting global warming is considered and other factors such as methane and N_2O are excluded. For example, the global warming effect of methane is about 25-30 times stronger than that of CO_2. Therefore, in order to use LNG made of methane as marine fuel instead of HFO, environmental evaluation and regulation of methane are also required. From a point of life cycle perspective, the actual result of it cannot achieve IMO's GHG strategy (Pavlenko, Comer, Zhou, Clark, & Rutherford, 2020). Specifically, Figure 1-3 shows the follow-up actions and timelines for achieving the IMO initial strategy. Based on the information collected by the data collection system (DCS) from 2019 and the results of the 4th IMO GHG study, a revised IMO GHG strategy will be prepared in 2023, and candidate actions will be divided into short-term, medium-term, and long-term (MEPC73, 2018). As a part of this result, the development of life cycle greenhouse gas/carbon intensity guidelines for fuels was included in the initial IMO short-term strategy shown in Figure 1-3. The development of these guidelines would contribute to the identification and prevention of specific fuels that do not help reduce greenhouse gas emissions from a fuel lifecycle perspective. It is also able to provide diverse stakeholders with a clear understanding of the GHG/carbon intensity of fuels.

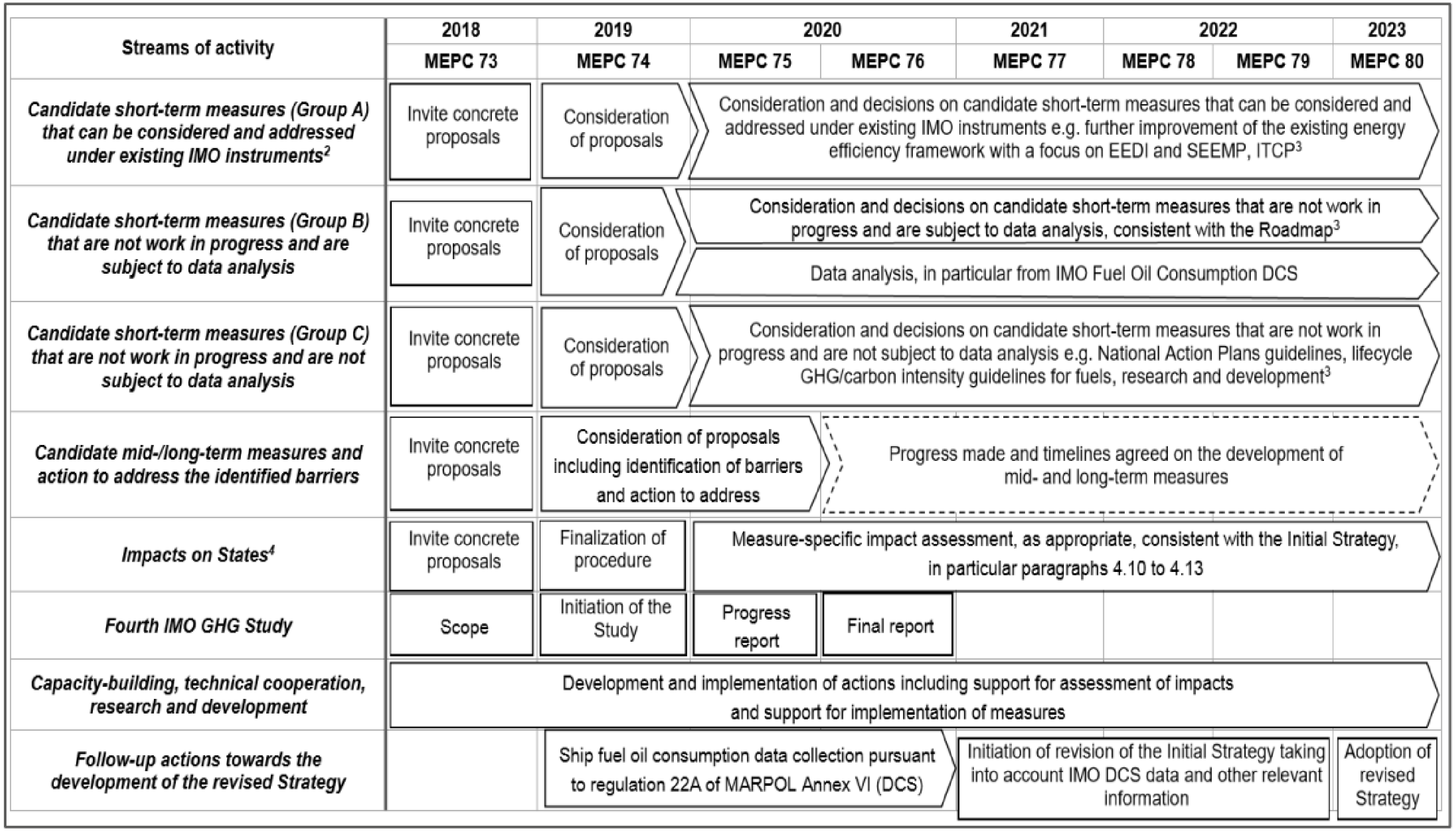

Figure 1-3: Follow-up actions & programs (MEPC73, 2018).

- The fact that the current shipping environmental regulations focus only on operation phase can also be the motivation of this research. For example, Figure 1-4 shows the simplified life cycle pathway of hydrogen in shipping sector. When hydrogen is used as a fuel for ships, the process of using hydrogen on ships is expected to be very environmentally friendly. However, since more than 90% of hydrogen in the world is currently produced based on fossil fuels, there is a high possibility that numerous emissions will be emitted during this process (Dincer & Acar, 2015). In the end, since current rule and guideline perspective is too narrow, the entire production process as well as the total emission used in ships must be analyzed and evaluated to determine hydrogen is more eco-friendly than the existing HFO. In other words, the maritime emissions need to be evaluated in a broader and holistic perspective in recognition with each life stage of a ship and/or a system contribute to generating emissions. To respond to such a demand, the life cycle assessment (LCA) has been introduced as an optimal solution for the marine industry.

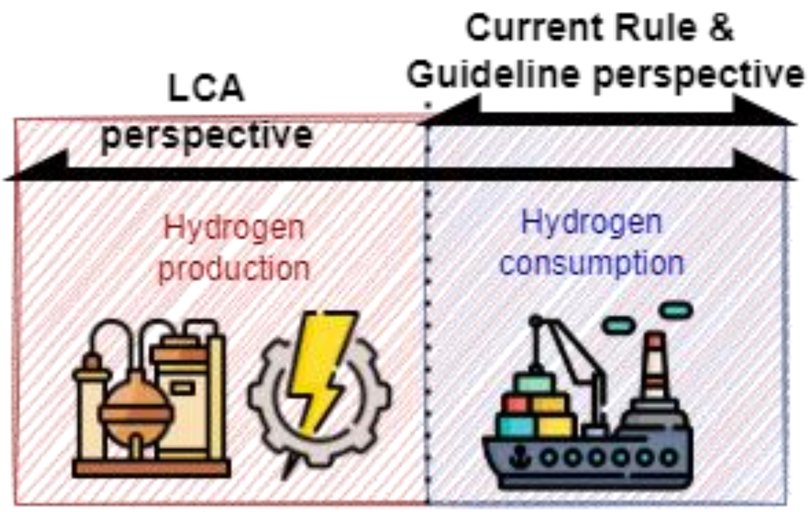

Figure 1-4: Comparison LCA scope with current rule & guideline scope in hydrogen pathway.

- In addition, since basic information such as age, power, and tonnage, as well as geographical characteristics of sailing are different for each ship, the most suitable eco-friendly fuel and system considering the characteristics of each ship must be applied. However, it is not yet possible to answer which of the many alternative fuels and systems currently available would be the greenest solution for a particular vessel. As such, it is still at a difficult point to make decisions about eco-friendly alternatives for various stakeholders who may lack an understanding of the environment.

Summarizing these critical limitations now raises the question of whether current shipping environmental regulations and approaches are complete. In order to properly establish the awareness of eco-friendly fuels and systems and to have the right direction for environmental policies, several current shipping environmental regulations need to be reviewed and the limitations of the several approaches identified in this project must be overcome.

1.4. Outline of the thesis

This thesis consists of 8 chapters and 3 appendices. This section briefly describes the contents of each chapter:

- **Chapter 2** offers the research aim and objectives based on the issues presented in Chapter 1. As already revealed, serious environmental crisis caused by global warming and air pollution from shipping has been introduced. Although numerous solutions have been proposed to overcome this crisis, it has still many problems such as narrow environmental perspective, inherent limitation of current marine environmental assessments. Thus, the main aim of this PhD thesis was to contribute to introducing an LCA-based methodology for assessing the environmental impacts of marine fuels and systems.

- **Chapter 3** introduces various environmental analysis tools and rationally suggests the necessity and importance of LCA to achieve the goal of this project. This is because LCA is an analytical tool, not a procedural tool, that enables quantitative environmental evaluation and is suitable as a methodology to achieve the aim and objective of this project with a broader perspective. In addition, the information regarding the background of LCA with a brief history and the available literature review of all aspects of the LCA publications. As the use of LCA has been expanded, it is also widely used for environmental evaluation in shipping, but the limitations that are difficult to use from a more general point of view are reviewed due to limitations due to case scenario-based research.

- **Chapter 4** shows the general process and more detailed explanation of Parametric Trend LCA (PT-LCA), which was developed appropriately to achieve the aim and objectives of this project by overcoming the limitations of LCA introduced in Chapter 3. In addition, the difference between PT-LCA and conventional LCA was shown.

- **Chapter 5** provides the first case study of applying PT-LCA to scrubber systems. By implementing PT-LCA on more than 1,000 ships, the correlation between ship information and ship environmental impacts and whether it is applicable to the system were identified.

- **Chapter 6** provides the second case study in which PT-LCA is applied to LNG fueled ships, and it is confirmed whether PT-LCA is applicable not only to the system but also to alternative fuels. Through comparative analysis by various ship types and engine types, the importance of the impact of fuel supply methods on eco-friendliness was revealed.

- **Chapter 7** provides the third case study of the application of PT-LCA to hydrogen fuel cells, and it was confirmed whether PT-LCA could be applied to alternative fuels and systems still under development. Various hydrogen production methods and fuel cells were applied to about 2,000 ships and compared and analyzed in terms of life cycle perspective.

- **Chapter 8** covers the discussion part covering the novelty, contributions and limitations of this research and suggests practical guides for future works. Also, this chapter summarizes the main insightful conclusions through this research work.

Appendices A & B provide supplementary information not included in the main text as follows:

- **Appendix A** provides LNG fuelled vessels environmental impact trends.
- **Appendix B** provides hydrogen fuel cells environmental impact trends.
- **Appendix C** provides related overview references and long tables.

2. THESIS AIM AND OBJECTIVES

2.1. Aim and objectives

The main aim of this PhD thesis was to develop LCA-based methodology for parametric trend analysis to assess the environmental impacts of marine fuels and systems. In order to achieve this aim, the objectives set more specifically as below:

- Objective 1: To identify the research gap by examining the state-of-the art environmental assessment tools and improving the understanding of the background knowledge by conducting an extensive literature review.

- Objective 2: To develop and propose an appropriate method to fill the identified research gap overcoming current limitations observed in the literature review.

- Objective 3: To demonstrate the effectiveness of the proposed novel environmental assessment tool by quantifying lifecycle benefits/harms of various alternative marine fuels and systems to enhance the general environmental understanding for cleaner shipping.

- Objective 4: To suggest future research work and regulatory frameworks by covering the research gap to contribute to the future environmental fuels and systems for cleaner shipping.

2.2. Tasks

In order to achieve the research aim and objectives, some specific tasks should be considered and conducted as below. Figure 2-1 shows the overall structure of the research work.

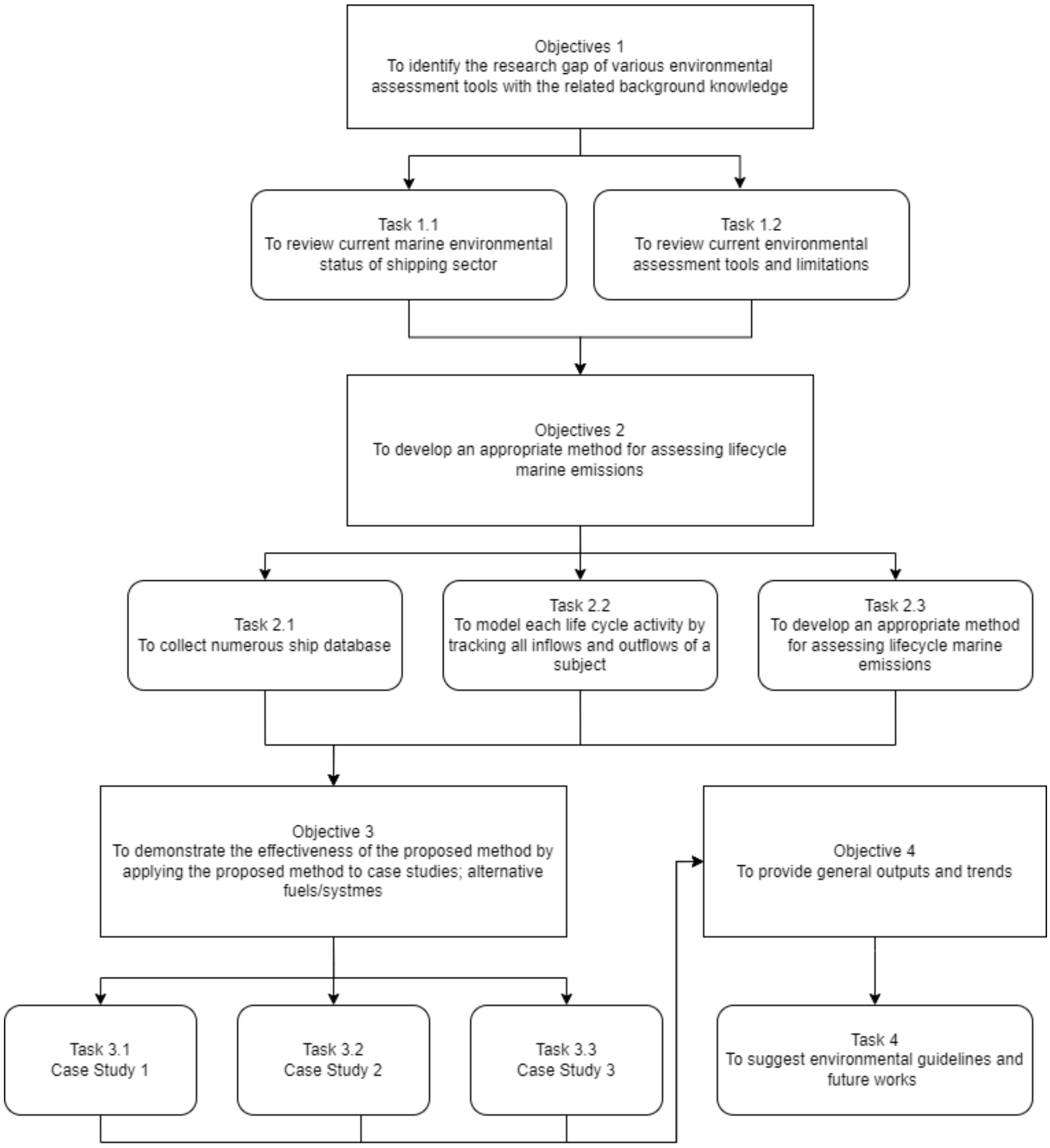

Figure 2-1. Outline flowchart for the research work.

Task 1.1 Overview of current environmental status of shipping sector

The current main issues regarding environmental impacts of shipping sector were identified and corresponding countermeasures in terms of current regulatory frameworks and various alternative fuels and systems were examined. As an environmental assessment method, LCA and its inherent limitation were introduced.

Task 1.2 Literature review

Various environmental analysis tools to measure the eco-friendliness of representative alternative marine fuels and systems to cope with the increasingly serious environmental problems of shipping were reviewed. Also, with a brief history of LCA, the extensive and in-depth LCA literature review was conducted in terms of application in various fields including marine sector. Above all, the limitations of LCA shown mainly in the marine sector were examined and studies were introduced to contribute LCA to general policy rather than simply an environmental assessment tool.

Task 2.1 Database collection

To overcome the intrinsic limitations of conventional environmental assessment, it is necessary to collect numerous ship databases to derive general observations. Unlike conventional methods, the proposed method combines much larger and more extensive data to process multiple case studies simultaneously.

Task 2.2 System platform modelling

The types and quantities of emissions pertinent to each activity are estimated by tracking all inflows and outflows of product systems, including raw materials, energies, and emissions from certain substances. This kind of analysis is regarded complex as possibly including dozens of individual unit processes in the supply chain. To facilitate the analysis, the LCA was implemented in the 'LabVIEW' platform in connection with the data library. Ship information stored in the data library as input parameters for the analysis is fed into the analysis platform which encapsulates the life cycle inventory (LCI) models and algorithms for quantifying energy consumption and emission levels.

Task 2.3 Parametric trend analysis

The parametric trend analysis can be regarded as generalisation process. It is because the individual results generated from repeatable LCA processes are consolidated to represent a general trend which can offer an insight into the relationship between the subject systems and mother ships in terms of environmental benefits. These correlations are formulated into equations as LCA equations for estimating the overall environmental impacts of marine systems straightforwardly. It can be greatly supportive of regulatory framework and decision-making on system selection. Indeed, it enables stakeholders who are not familiar with LCA can obtain LCA results.

Tasks 3.1 - 3.3 Environmental impacts of selected representative alternatives

Some insightful case studies were conducted by applying the novel proposed method. Through this process, the developed method can be proved in terms of validation and effectiveness showing the meaningful results of those case studies which can provide deeper understanding regarding marine environmental impacts.

Various solutions have been proposed in shipping and divided into mainly three methods which are engine change, fuel change, and installing an additional end-of-pipe system. Therefore, this project reviewed whether various green shipping solutions can be applied by applying the proposed methodology to these three methods. Scrubber systems, LNG, and hydrogen were selected as the subjects of case studies representative marine future fuels and systems among the alternatives. Below is a brief elaboration of each fuel and system selected for the project.

Task 3.1 Scrubber systems

In order to examine whether PT-LCA is applicable in terms of the system, a scrubber system, one of the representative systems, was selected. Although the scrubber system is a system used to reduce SOx emission from ships, it was selected as the first case study of this project because it is expected to have a significant impact on the environment in various aspects including global warming.

Task 3.2 LNG fuel

It was conducted to explore whether PT-LCA is applicable to the method of replacing marine fuel among the solutions for green shipping. Thus, LNG fuel which is a representative alternative ship fuel was selected as the second case study. It is currently attracting attention as the most realistic eco-friendly alternative fuel that can dramatically reduce SOx and NOx emissions while replacing HFO and is widely used as a bridge fuel for future alternative fuels.

Task 3.3 Hydrogen fuel cells

It was examined whether PT-LCA is applicable not only to both fuel and system aspects, but also to cases that are still under technological development. Hydrogen fuel cells were selected for this case.

Task 4

The results obtained from the PhD thesis were reviewed for general observation and insight, and their applicability to environmental guidelines and regulations was examined. In addition, the limitations of this study were identified, and the direction of the next future research was suggested.

3. LITERATURE REVIEW

This project was initiated to develop LCA-based methodology for parametric trend analysis to assess the environmental impact of marine fuels and systems. In this context, this chapter tried to critically review the existing efforts to contribute to the environmental assessment in marine by evaluating the ideas and information of the existing papers to confirm the information already known about the subject and the information obtained through it. Therefore, a brief description and characteristics of the overall environmental assessment tools are introduced, and the current position of LCA is identified through the similarities and differences between the assessment tools. This section is also designed to identify the importance and limitations of LCA through a brief history and application areas and roles in shipping.

3.1. Environmental analysis tools and LCA

3.1.1. Needs for environmental analysis tools towards policy making

As environmental pollution becomes more serious, the importance and the use of environmental assessment have increased. Accordingly, efforts have been made to find ways to improve environmental systems and minimize environmental pollution by investigating, predicting, analyzing, and evaluating the impact on the environment through environmental evaluation in advance.

Tools for analyzing the environmental impact of the system are very diverse and can be divided into procedural tools for environmental policy and decision-making such as environmental impact assessment (EIA), strategic environmental assessment (SEA) and environmental management system (EMS), or analytical tools used when considering technical aspects for environmental analysis results. The following is a brief description of several representative environmental impact analysis tools, along with a discussion of the limitations of each tool.

(a) *Overview of environmental analysis tools*

Environment Impact Assessment (EIA)

Environmental Impact Assessment (EIA) is used to predict and evaluate environmental impacts when a government agency or private sector establishes a large-scale development project plan to make decisions such as the feasibility of the plan and location. This could be, for example, the construction of a new airport or highway, as well as other more decentralized projects. EIA has evolved as the industrial society's development projects have had a profound impact on environmental pollution.

The general process for EIA is as follows: Project screening to evaluate whether EIA is a required project, scoping to determine what are the major impacts and issues to be considered in EIA, reviewing alternatives, and analyzing environmental impact within the scope of the project, and finally, making decisions about forecasting and mitigation measures (Rybaczewska-Błażejowska & Palekhov, 2018).

The basic principles of EIA are: First, measures should be taken to avoid or reduce harmful environmental impacts from the implementation of projects subject to environmental impact assessment to the extent economically and technologically feasible. Second, environmental conservation measures are based on scientifically investigated and predicted results. Third, efforts are made to provide sufficient information on projects subject to environmental impact assessment so that residents can smoothly participate in the environmental impact assessment process.

However, as the EIA is one of the oldest frameworks for political decision-making on environmental impact, legislation at the European level has been amended several times. Nevertheless, since the environmental impact assessment still only analyzes a very limited range of space and time, the indirect effect of the project may be higher, but it is pointed out as a limitation that it is mostly ignored in the environmental impact assessment (Tenney, Kværner, & Gjerstad, 2006).

Strategic Environmental Assessment (SEA)

SEA is a decision-making process that considers the environmental impact of policies, plans and programs for sustainable development.

The term 'strategic environmental assessment' first appeared in the European Commission in the late 1980s, and various types of directives are being developed together with the EU Directive. Because SEA is used at a strategic level, the exact location of various emission sources is known, a feature that may require different assessment methods compared to more traditional EIA.

SEA is a proactive approach that influences the early stages of decision-making (Sadler, 1996). In addition, SEA is a representative procedural tool and change-oriented research that ultimately aims to integrate a wide range of national-level policies, plans and programs. Therefore, the SEA should be able to consider the various possible futures as part of decision making rather than a tool for analyzing and evaluating the outcome of decision making. To achieve this, the use of SEA through scenario development is widely recommended.

Life cycle assessment (LCA)

LCA is an analytical tool that identifies environmental impacts and quantifies the emissions of environmental pollutants and resources and energy used in all stages of products and services, from raw material acquisition to transportation, production, use, and disposal. As such, LCA is a very detailed in-depth analysis, whereas EIA and SEA are procedural tools that only consider the emissions and impacts that occur at the location of the project, so it is likely to ignore the actual environmental impact to a large extent. The goal of LCA is to minimize environmental pollution through the life cycle evaluation of products and materials to realize environmentally sound and sustainable development. Procedures and methods have been standardized as part of the establishment of the ISO environmental management standards (ISO 14000 series). As a result, it is possible to help determine strategic priorities for the environment by understanding the environmental impact of the product's entire life cycle, and to manage it more efficiently by organizing environment-related data.

(b) Attempts to introduce LCA in EIA and SEA

As already mentioned, life cycle perspective policy is required. Thus, the importance of utilizing of LCA is increasing. However, as an analysis tool, not a procedural tool, LCA has limitations in making policies reflecting the life cycle perspective.

For this purpose, there have been numerous attempts to introduce LCA in EIA and SEA as below.

Tukker (2000) argued that EIA must include a systems approach that takes into account all relevant effects, such as LCA, in order for alternatives to be comparable, and shows an example applied to Dutch national waste management plans.

Obersteiner, Binner, Mostbauer, and Salhofer (2007) showed the application of LCA to SEA to evaluate the management system for transporting waste to landfills from various perspectives.

Larrey-Lassalle et al. (2017) has proposed a comprehensive operational methodology for conducting a LCA within an EIA process. This approach was implemented as a case study approach comparing a wastewater treatment plant (WWTP) project with an existing EIA study that considered LCA and demonstrated feasibility for LCA.

In this context, procedural tools such as EIA, SEA can be used to efficiently calculate and evaluate environmental aspects related to production processes. However, these tools are inherently limited in focusing only on specific regional programs rather than assessing the impact of endpoint environments such as carbon footprint (Fet, Aspen, & Ellingsen, 2013). Thus, this attempt is not able to fulfil the aim of this project.

3.1.2. Background of Life Cycle Assessment

(a) Brief history of LCA method

As can be seen in Figure 3-1, LCA is a tool that quantitatively evaluates all stages of the life cycle from a cradle to grave point to assess the potential environmental impact of a product or service, such as resource use, human health, and ecological consequences. In general, LCA standardized by International Organization for Standardization (ISO) is classified into ISO 14040, which summarizes the concept, and ISO 14044, which describes the methodology for measuring eco-friendliness in various fields (ISO, 2006).

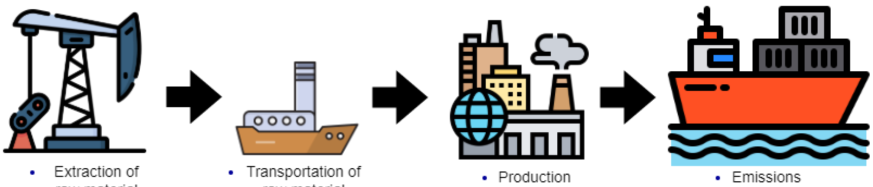

Figure 3-1: The life cycle of marine fuels (Andersson, Brynolf, Landquist, & Svensson, 2016).

Table 3-1 shows the chronological review of overall LCA history. The first studies that are now recognized as LCA back to the late 1960s and early 1970s. LCA development began in the early 1970s due to depletion of natural resources, increasing awareness of energy efficiency and growing waste problems. In addition, after the first oil shock of 1973~1974, those who identified the vulnerability of an industrial society heavily dependent on crude oil naturally increased their interest in energy supply.

Therefore, the scope of these studies was initially limited to energy analysis, but later expanded to include resource requirements, emission loads, and waste generated. Early LCA studies from this period were primarily conducted on waste treatment and were specifically applied to beverage packaging comparisons (Corporation & Curran, 2006). Against this background, the first LCA in its modern sense was a proto-LCA named Resource and Environmental Profile Analysis (REPA), which was a lifecycle inventory analysis without impact assessment (Guinee et al., 2010).

However, the approaches and terms used in each of the LCA studies were still diverse, and there was no common framework, so it was difficult to apply them in general despite the same study subjects. At the same time, as the impact of the oil shock diminished, interest in LCA began to diminish. However, as the amount of accumulated waste increased in the late 1980s, LCA research began to flourish again (LeVan, 1995).

In the 1990s, as interest in LCA grew significantly in Europe and North America, there was a worldwide effort to standardize LCA methodology beyond inventory and practically through various workshops and other forums. The ultimate goal of these meetings is to refine the methodological refinement of LCA and to establish a unified approach and procedure (Hunkeler & Rebitzer, 2005).

Among them, the society of environmental toxicology and chemistry (SETAC) most actively defines LCA as an organization to create a uniform framework methodology, which analyzes the flow of input and output of total energy of a target system. Accordingly, the methodology for evaluating the environmental impact by classifying weights according to the environmental impact of each energy input and output of the system has been systematized.

SETAC's LCA system developed in this way was standardized by ISO and has been officially maintained through the 14000 series from 1997 to 2002 (Guinee et al., 2010). The standards for life cycle assessment are composed of ISO 14040:1997, ISO 14041:1999, ISO 14042:2000 and ISO 14043:2000 (ISO, 2006), defining principles and frameworks, goals and scope, respectively. In addition, inventory analysis, life cycle impact assessment, and interpretation are considered, contributing to the integration of existing LCA procedures and methods (Guinee et al., 2010).

The importance of standardized LCAs began to become increasingly influential in global environmental policies, typically lifecycle-based carbon footprint standards. Since ISO 14040 states that “there is no single way to perform LCA”, although LCA has been standardized by ISO, various approaches have been developed to address the details (ISO, 2006). As such, the methodology became sophisticated, with a focus on the US and Europe encouraging the use of platforms. This eventually led to LCA being applied across various industries such as goods and services, manufacturing, construction and education (Chang, Lee, & Chen, 2014; Westkamper, Alting, & Arndt, 2000). In addition, life cycle-based techniques such as life cycle costing (LCC) and social life cycle assessment (SLCA) have been developed for comprehensive use that integrates economic and social concerns beyond simply applying LCA to environmental aspects (Chang et al., 2014; Norris, 2001; Rebitzer & Hunkeler, 2003).

Recently, as LCA began to be developed in a wider range, the concept of sustainability was introduced to achieve the ultimate eco-friendliness and expanded to life cycle sustainability analysis (LCSA), which is a main trend with more attention.

Table 3-1: the overall LCA histroy with trajectories and drivers in LCA development (Blanco-Davis, 2011; McManus & Taylor, 2015).

Trajectories	Drivers		Year	Individuals/Organisations	Event	Place
1970-1990: Decades of conception	Company driven	Single issues and products	1963	Harold Smith	Calculation of cumulative energy at World Energy Conference	U.S.
			1969	The Coca-Cola Co.	Performed 1st LCA	U.S.
		Product policy	1970s		Oil Crisis Era: focus on energy supply and demand	Int'l
			1972	Ian Boustead	Development of Ecobalance	Europe
			1972	Meadows et al.	Published The Limits to Growth	U.S.
			1972	Goldsmith et al.	Published A Blueprint for Survival	U.S.
			1970-1975		REPAs and Ecobalance: Quantification of resource use and environmental releases	U.S. and Europe
			1979	Ian Boustead	Published the Handbook of Industrial Energy Analysis	Europe
			1975-1980s		Oil Crisis Era ends: interest in LCA decreases	Int'l
			1980s	European Commission	Establishment of an Environment Europe Directorate (DG X1), increases LCA interest	Europe
			1988		Solid waste worldwide issue: LCA emerges as a tool for analysing environmental problems	Int'l
1990-2000: Decade of standardization	Regulatory/ Compliance driven	Pollution prevention	1991	SETAC	Published A Technical Framework for Life Cycle Assessment	U.S.
			1992	U.N. Earth Summit	LCA emerges as a prominent tool for environmental management tasks	Int'l
			1993	SustainAbility, SPOLD and Business in the Environment	Published The LCA Sourcebook	Europe
			1993	SETAC	Published Guidelines for Life Cycle Assessment: A Code of Practice	U.S.
			1993	Keoleian et al.	Published Life Cycle Guidance Manual	U.S.
			1994	Vigon et al.	Published Life Cycle Assessment: Inventory Guidelines and Principles	U.S.
			1996	Curran, M.A.	Published Life Cycle Analysis	U.S.
			1997	SETAC	Published Life Cycle Impact Assessment: The state-of-the-Art	U.S.
			1997-2002	ISO	Published 14000 series including ISO 14040:1997, ISO 14041:1999, ISO 14042:2000 and ISO 14043:2000	Int'l
			2006	ISO	Revision, cancellation, and replacement of previous LCA standards. Published current ISO standards 14040:2006 and ISO 14044:2006	Int'l
2000-2010: Decade of elaboration	Policy driven	(Energy) Policy development			LCA in energy policy, especially biomass and biofuel US: LCA for market access across state lines UNEP/SETAC initiative to look at social LCA	

(b) ISO LCA standards

To respond to such a demand, the LCA has been introduced as an optimal solution for the marine industry.

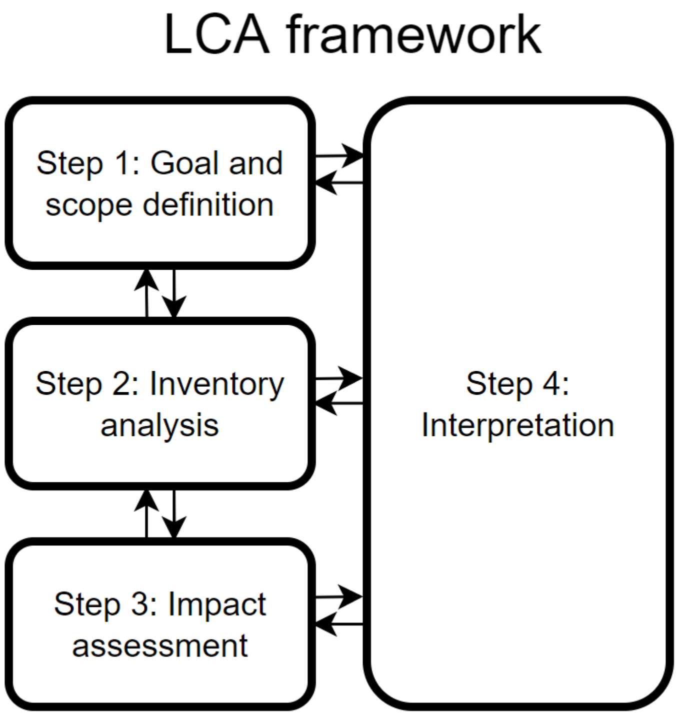

Figure 3-2: LCA phases according to ISO 14040:1997/2006.

Figure 3-2 shows the basic process of LCA specified in the ISO Standards (ISO, 2006): the establishment of the goal and scope (Step 1), Life Cycle Inventory (LCI) (Step 2), Life Cycle Impact Assessment (LCIA) (Step 3) and Interpretation (Step 4).

Step 1. Define Goals and Scope: This step defines the system boundaries and the levels of detail as well as scope. For example, goals vary depending on the research topic and intended use. Thus, the depth and width of the LCA will depend accordingly (ISO, 2006).

Step 2. Life Cycle Inventory Analysis (LCI): It consists of an inventory of input and output data related to the system being evaluated. It also includes gathering the necessary data to meet the requirements previously defined by the research objectives (ISO, 2006).

Step 3. Life Cycle Impact Assessment (LCIA): The purpose of this step is to evaluate the LCI results of a product system to provide additional information with a clearer understanding of its environmental significance (ISO, 2006).

Step 4. Interpretation: The final step is to interpret the research results and the previously defined research goals and scope (ISO, 2006).

In the goal and scope phase, once the system boundary of the research subject is established, the energy and emission data input to the raw materials constituting the system is standardized as a unit mass for each stage.

As such, life cycle inventory analysis (LCI) quantitatively calculates the environmental impact that occurs throughout the product life cycle, so the data collection step is necessary to quantify information about a single stage in the life cycle system. In this case, the data type can be either quantitative or qualitative, usually by listing the input and output of all materials and energy to the system in a table.

In the impact assessment phase, the various emissions quantified in the inventory analysis phase are classified and characterized into various impact categories.

For example, Global Warming Potential (GWP) is an indicator of the potential for greenhouse gas emissions and is affected by emissions such as CO_2, CH_4, and N_2O. Therefore, this classification of impact categories makes it more intuitive and easier to interpret information about the results of the various emissions organized in the inventory analysis phase as a result.

Finally, in the interpretation phase, it summarizes and interprets the results of inventory analysis and impact assessment to make conclusions and recommendations for the study.

3.1.3. Concluding remarks

As the climate crisis and environmental pollution become more serious, interest in environmental analysis is increasing. Various environmental analysis tools exist for different purposes. However, they cannot satisfy the needs of various stakeholders in the current shipping industry and have inherent limitations to apply to general maritime regulations or policies. Amongst them, it was revealed that the most appropriate methodology is LCA.

3.2. Overview of LCA application

3.2.1. Application of LCA

This section shows how LCA has been utilized in diverse areas. Figure 3-3 is a graph of the number of scholarly literatures on LCA in the Scopus database from 1990 to 2020. Beginning in the 1990s, the interest in the academic literature on LCA shows an explosive increase. Since 2010, more than 1,000 publications have been published, and it can be seen that interest in and the use of LCA has rapidly expanded. This suggests that the awareness of LCA is starting to take on academic significance, as it has attracted attention due to the seriousness of climate change and environmental problems.

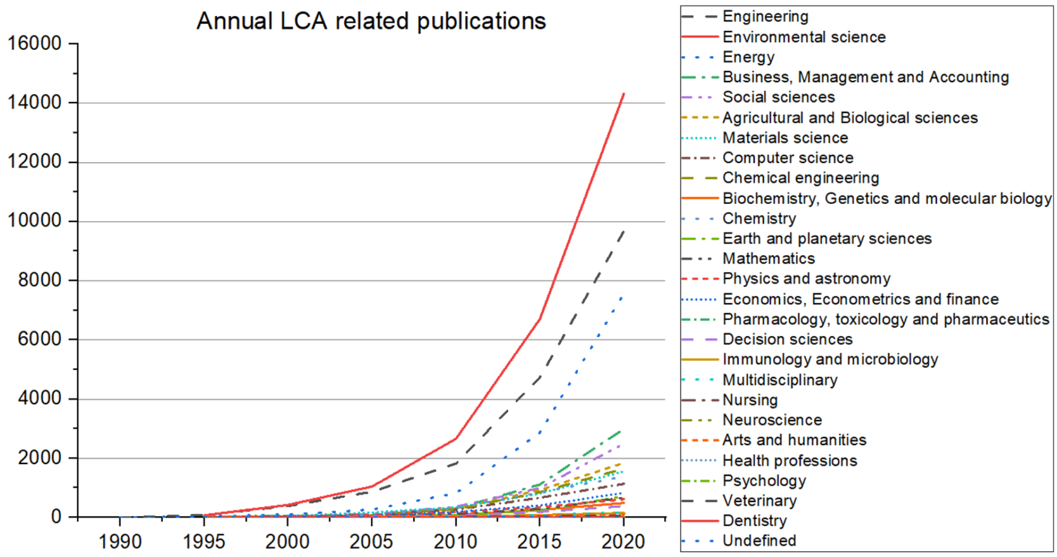

Figure 3-3: Annual LCA related publications.

Figure 3-3 shows that since 2005, LCA has been applied in a very wide range from engineering to energy, arts, humanities, and health issues. LCA is most widely applied in engineering and environmental science. In particular, the rapid increase in LCA research in the field of environmental engineering and energy in 2010 shows that it is contributing more to the environment and energy fields than before.

Likewise, many of the current energy-related LCA studies are closely related to greenhouse gases, and in 2010, they overtook waste-related studies in LCA issuance records (Union, 2009). In terms of the history of LCA as a methodology that began in waste and packaging analysis, its extension to comparative studies of greenhouse gas sources suggests a further growing influence of LCA. In addition, this fact is expected to have a significant impact on LCA research due to the growing interest in environmental and energy policy development. As LCA is a useful tool for driving and shaping policies, Figure 3-3 shows how social science expanded the use of LCA. In addition, since 2010, as interest in social and ecosystem service metrics has grown significantly.

3.2.2. Application of marine LCA

As LCA has been applied to shipbuilding as much as it has been applied in various fields, attempts have been made to become a new turning point in reinterpreting the environmental impact assessment method of ships and shipping in a different way than before. The next section seeks to explore how LCA has been applied in shipping by providing some of the published work.

As shown in Table C 1, the first author to apply LCA to shipping was Professor Fet, who has conducted extensive research in the shipping field since 1996. The author first wrote a study to implement LCA and LCC in a platform supplying vessel, emphasizing the importance of the environmental impact generated by the vessel, and stating that the emission generated from the vessel should be minimized (Fet, Emblemsvåg, & Johannesen, 1996).

Fet and Sørgård (1998) also reviewed how ISO 14000 related to LCA was implemented in the Norwegian shipping and shipbuilding sector through a case study. Some of the key findings of the study revealed that the operational phase of a ship is most important in terms of its contribution to environmental impact. This study emphasized the importance of continuous accumulation of related databases and development of ship-related LCA analysis software.

Meanwhile, since there are many methodologies for dealing with environmental impacts arising from shipping, but no equivalent holistic approach used in the maritime sector, the authors have presented a life cycle environmental management framework for ship design that can be agreed upon by multiple stakeholders (Fet et al., 2013).

Since then, interest in marine LCA has continued to increase, suggesting a design to minimize energy consumption and environmental impact generated during ship building, operation, and dismantling, emphasizing the rationality of materials used in ships. Consequently, the importance of using LCA to improve the environmental performance of ships has been emphasized (Shama, 2005).

As an important study in this regard, Jivén et al. (2004) conducted a project to collect data and develop an LCA analysis methodology for ship transportation. As a result, a software tool called LCA-ship was developed, and similarly, there is a case study in which environmental impact analysis was performed on actual bulk carriers by developing LCA software specialized for Japanese conditions by Kameyama, Hiraoka, and Tauchi (2007).

However, although LCA-related research has increased in shipping, IMO is still developing and using EEDI and EEOI as tools to improve shipping environmental efficiency. Thus, Blanco-Davis and Zhou (2016) conducted a study comparing the LCA approach with IMO regulatory indicators currently used . As a result, unlike the existing EEDI and EEOI, LCA can provide not only CO_2 but also NOx and SOx information and aids to efficiently use detailed environmental information according to the entire lifespan of the vessel and the design stage. It was also concluded that the LCA methodology could be of great help in monitoring and reporting environmental emissions from maritime transport.

As part of efforts to minimize emissions from ships, LCA research on marine technologies or alternative propulsion systems to increase efficiency and development of alternative fuels for ships has been actively conducted since about 2010.

As a representative study of ship replacement propulsion systems, Alkaner and Zhou (2006) published a molten carbonate fuel cell (MCFC) plant for marine applications and the reuse of hydrogen-powered fuel cells through LCA of a conventional diesel engine (DE). As a result, this research reveals that recycling is more environmentally friendly than conventional diesel engines. On the same line, Strazza, Del Borghi, Costamagna, Traverso, and Santin (2010) compared and analyzed a wider variety of fuel options such as methanol, bio-methanol, natural gas and hydrogen, with the scenario of using a solid oxide fuel cell (SOFC) rather than an MCFC as an auxiliary power system for ships. The analysis results highlight that the fuel production stage has a strong influence on the life cycle impact and that bio-methanol supply is a very attractive solution from a life cycle point of view.

LCA research on alternative marine fuels for ships as well as marine technologies has been particularly active. Corbett and Winebrake (2008) conducted an environmental analysis comparison of marine gas oil (MGO), marine diesel oil (MDO), and residual oil (RO), which are in the spotlight to achieve a reduction in SOx emission from ships, showing that MGO and MDO were 70-85% of SOx emission reduction achievement higher than RO. As a result, they can contribute to estimating environmental impacts related to fuel conversion and emission control policies. To achieve this goal, a container vessel traveling between Hong Kong and Los Angeles, a life cycle assessment was performed as a case vessel.

After that, the major contributor to the most ground-breaking role in the LCA research on marine alternative fuels was arguably Selma Brynolf. As her interest in air emissions from ships increased starting in the 2010s, her extensive LCA research played an important role on marine LCA alternative fuels.

Specifically, S. Bengtsson, Andersson, and Fridell (2011) compared and analyzed HFO, MGO, gas-to-liquefied (GTL) fuel and LNG and two emission reduction technologies (open scrubber and selective catalytic reduction) from a life cycle perspective. As a result, it was found that LNG and other alternatives can significantly reduce acidification and eutrophication than HFO, but LNG does not reduce GWP due to methane slip. To achieve this goal, the life cycle assessment was performed using a Ro-Ro vessel with a total engine capacity of 14,680 kW.

In a similar study, Laugen (2013) compared the marine fuels LNG and HFO with respect to their environmental performance from a life cycle perspective. The impact categories selected for LCA were global warming potential (GWP), acidification potential (AP) and primary energy use. It was assumed that natural gas would be supplied from Statoil's Melkøya plant in Norway, transported on LNG carriers to Rotterdam, and then used as marine fuel for passenger ferries departing from Rotterdam.

HFO, on the other hand, was assumed to be extracted as crude oil in the North Sea and transported by tanker to Rotterdam, where it would be used as marine fuel for the same vessel. As a result, it turns out that LNG is slightly more eco-friendly from a lifecycle point of view than HFO (Laugen, 2013).

As another similar case study, a product tanker was set as a case vessel and compared and analyzed from the perspective of GWP among HFO, MGO, and LNG as ship fuel. A two-stroke engine with waste heat recovery (WHR) was found to be the most environmentally friendly propulsion method (Baldi, Bengtsson, & Andersson, 2013).

S. K. Bengtsson, Fridell, and Andersson (2014) further analyzed the comparative analysis of HFO, marine diesel, biomass-liquid fuel, rapeseed methyl ester, liquefied natural gas and liquefied biogas to be used in short-distance sea transportation from a life cycle perspective, and the impact of liquefied natural gas on the local environment. This study concluded that liquefied biogas is the most environmentally friendly when considering all environmental impact categories. A Ro-Ro vessel was selected for the study and assumed to be operated by sulphur emission control area (SECA) in Northern Europe during 2010-2020.

In addition, Brynolf, Fridell, and Andersson (2014) compared the life cycle environmental performance of LNG, liquefied biogas (LBG), methanol and bio-methanol. However, it is expected that the impact on climate change will be on the same scale as the use of heavy oil. It is the use of LBG and bio-methanol that has the potential to reduce climate impacts. For the evaluation of the whole process, it is assumed that the Ro-Ro vessel will be operated in ECA in Northern Europe from 2010-2020 as a case vessel.

In the meantime, when biofuels are used for the shipping industry, a life cycle assessment was conducted using a case ferry between mainland Sweden and Gotland Island. It was to compare the diesel fuel route and the gas fuel route. As a result, although the gas fuel route had a better overall environmental assessment than the diesel fuel route, the use of biofuels was found to be less environmentally friendly in all impact categories except for GWP (S. Bengtsson, Fridell, & Andersson, 2012).

In a similar study, Verbeek et al. (2011) conducted an LCA case study based on the assumption that LNG fuel supplied in three ways to three types of short-haul ships operating in the Netherlands is used. As a result, it was concluded that energy consumption can be reduced by more than 10% with a hybrid electric drive system using LNG as a ship fuel.

Recently, a comparative LCA study for various alternative marine fuels including biodiesel was conducted by Paul Gilbert et al. (2018), and as a similar study, El-Houjeiri et al. (2019) conducted LCA focusing on GHG emitted by marine alternative fuels. Kesieme, Pazouki, Murphy, and Chrysanthou (2019) focused on biofuel LCA study, emphasizing the importance of geographical location and cultivation systems, and drew positive conclusions about the impact of biofuel on shipping sustainability.

Above all, Jeong, Wang, Oguz, and Zhou (2018) advanced the LCA methodology by developing a more effective LCA framework that can rationally suggest the most optimal propulsion system for ships.

3.2.3. *LCA research & market trends on selected marine fuels and systems*

The previous section revealed the importance of LCA for this project and its active application in research related to the shipping environment. In this section, with the recent market trends of scrubber systems, LNG fuel, and hydrogen fuel cells, which are representative marine alternative fuels and systems selected for this project, the related LCA research and its limitations are described.

(a) Scrubber systems

The exhaust gas cleaning system (EGCS), known as 'scrubber', which can remove SOx and particulate matters (PM) contained in the exhaust gases of conventional engines or boilers by means of sea water, chemical or dry substances, has started to being introduced in the marine industry. Figure 3-4 shows that the increase in the number of scrubber systems applied to marine vessels over the last decade; prior to 2010, only 5 scrubber systems were applied to marine vessels, but as of 2018, the cumulative number of vessels to be installed or under contract has reached over 1,200 sets of scrubber systems with a more moderate pace.

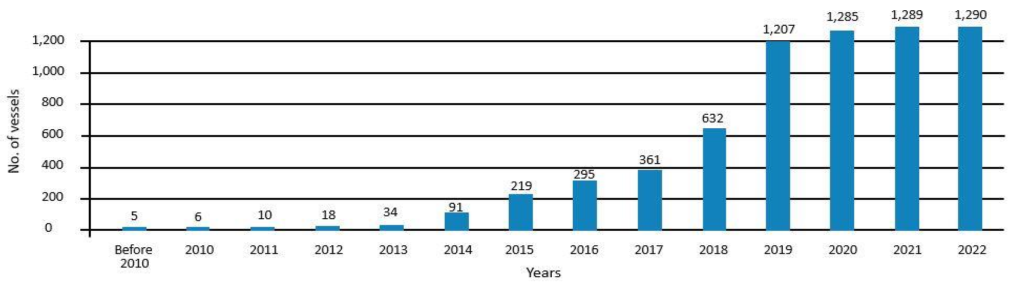

Figure 3-4: Scrubber systems market trend (DNV, 2018).

Along with the remarkable growth in the marine scrubber system market over a decade, a number of research on investigating the performance of scrubber systems has been conducted (AIR, 2016). However, the aim and scope of those past research and technical reports are highly focused on confirming the limits of SOx emission after treatment to certify the compliance of the SOx regulation. Although more than

30 manufacturers produce marine scrubber systems, there lacks research on quantifying the increment in the emission levels attributed by additional electricity consumption for operating the subject system. Meanwhile, in recent years, there has been a strong argument among IMO member states and stakeholders that the evaluation of shipping emissions should not only fall into the operation phase alone. In other words, the maritime emissions need to be evaluated in a broader and holistic perspective in recognition with each life stage of a ship and/or a system contribute to generating emissions. For example, if electricity is used to manufacture a scrubber system, emissions produced during power generation should be considered shipping emissions. To respond to such a demand, the life cycle assessment has been introduced as an optimal solution for the marine industry.

(b) LNG fuel

LNG fuel has been recognised as one of the most credible candidates as a bridge fuel to achieve green shipping (Sideri, Papoutsidakis, Lilas, Nikitakos, & Papachristos, 2021) It is because LNG has several advantages due to its relatively low energy price, lower sulphur content and low level of local emissions particles (Cepeda et al., 2019). Thus, the LNG market has continued to grow and expand rapidly, with major exports from Qatar, Australia, the United States, and the Russian Federation, driven by enormous global demand centred on Asia as shown in Figure 3-5(a), (b) (IEA & KEEI, 2019).

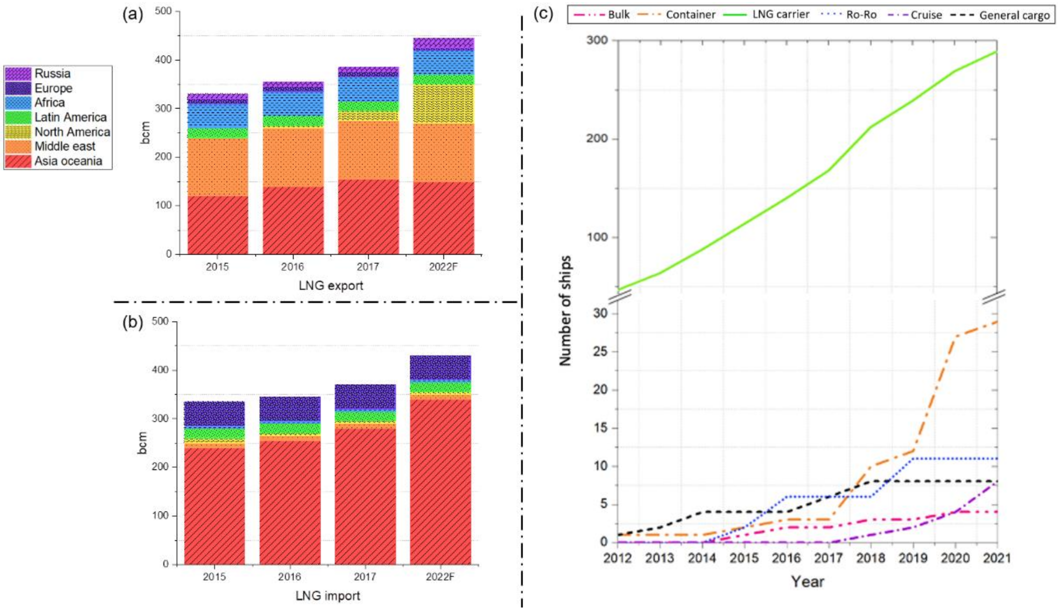

Figure 3-5: LNG supply and demand from 2015 to 2022 (forecast) (a), (b) (IEA & KEEI, 2019) & Cumulative LNG-fuelled ships built or on order as of mid-2018 (c) (Pavlenko, Comer, Zhou, Clark, & Rutherford, 2020).

In addition to LNG carriers, other vessel types that use LNG as marine fuel, such as bulk carriers, container vessels, oil tankers, and car carriers, have also started to increase at the initiative of Norway as shown in Figure 3-5(c) (Sharafian, Blomerus, & Mérida, 2019). It shows a 17% increase in the number of LNG-fuelled ships in-service and 36% increase in the number of those ships on-order in 2018 compared to 2017. This trend has continued over the last decade, as a result, the total number of LNG fuelled vessels has reached to about 350 ships including LNG carriers (Pavlenko et al., 2020).

With a strong popularity of LNG in the shipping industry, there have been voluminous environmental research in this field. Over the past decades, the energy industries have started to adopt LCA for estimating the holistic environmental impact of LNG using as a major national energy source (Tamura et al., 2001). Similarly, Okamura, Furukawa, and Ishitani (2007) conducted LCA to predict future LNG outlook, and Jaramillo, Griffin, and Matthews (2007) compared LNG with other alternative fuels which are coal, and Synthetic natural gas (SNG) for electricity generation. The automotive industries have also interested in using LCA as automotive fuel (Arteconi, Brandoni, Evangelista, & Polonara, 2010). Given this trend, the LCA has gradually obtained its reputation of being a useful tool to assess the environmental potential of natural gas holistically (Stamford & Azapagic, 2014). Prior to the 2010s, most studies reached similar conclusions, highlighting the potential benefits of using LNG as marine fuel in terms of environmental protection.

Since early 2010s, the first LCA research on marine LNG fuel has been conducted as a comparative analysis on different marine fuels: HFO, LNG, MGO, and GTL (S. Bengtsson et al., 2011). It revealed that LNG could reduce both AP and eutrophication potential (EP) by 78~90%, compared to HFO.

Later on, some other studies were followed in a similar range of studies; LNG was compared to other credible alternative fuels such as liquefied biogas, methanol and bio-methanol (Brynolf et al., 2014), biomass-to-liquid fuel and rape-seed methyl ester for short sea shipping (S. K. Bengtsson et al., 2014) and methanol as an alternative ocean shipping fuel (Paul Gilbert et al., 2018). Those studies have also drawn similar conclusions in favor of using LNG as a marine fuel.

In the meantime, since late 2010s when the negative impact of methane was seen as a major contributor to GWP, the effect of accidental methane release from LNG processes (Yuan, Ou, Peng, & Yan, 2019) and onboard gas engines (Pavlenko et al., 2020) has drawn more serious attention than ever before. This technical issue known as 'methane slip' occurs mainly when the unburnt fuel is released to the atmosphere due to incomplete combustion in Otto cycle engines, resulting in a greenhouse effect that is about over 25 times greater than CO_2 (Herdzik, 2018). Thus, it has been thought that using LNG as a marine fuel may possibly be more harmful than helpful in the environment; this finding is contrary to what was promised with LNG in the past studies in early 2010s.

In fact, several research have shown that LNG may not be the key alternative energy source. For example, Sharafian et al. (2019) showed the result that MS-LPDF engines and lean burn spark-ignited (LBSI) engines cannot curtail GHG emissions. Similarly, Pavlenko et al. (2020) evaluated 20- & 100-year GWP time frame for LNG engines and concluded that LNG cannot satisfy with green shipping.

(c) Hydrogen fuel cells

Hydrogen fuel cells have been hailed as one of the most promising alternatives for meeting those tough laws and worldwide environmental protection trends (Yan et al., 2020). As shown in Figure 3-6, low-carbon hydrogen production is expected to continue to increase as ten governments around the world adopt a hydrogen strategy. In particular, the amount of low-carbon hydrogen used for refining will increase from 250 in 2019 to more than 300 in 2020 (IEA, 2021). As a result, hydrogen fuel cells are being viewed as a viable future marine solution, as they provide great efficiency while reducing ship emissions (Yan et al., 2020).

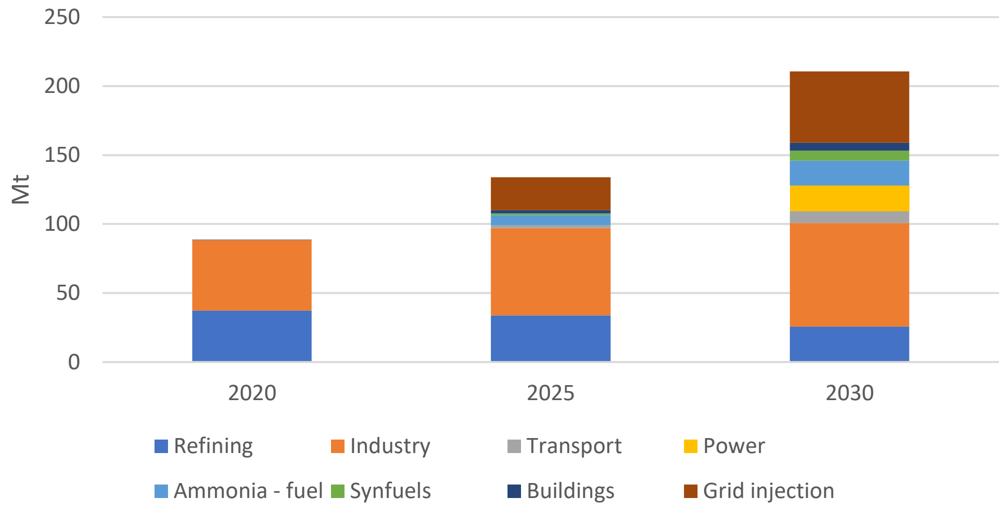

Figure 3-6: Global hydrogen demand by sector in the Net zero scenario, 2020-2030 (IEA, 2021).

There have been several attempts to investigate the environmental performance of hydrogen from a life cycle point of view. Koroneos, Dompros, Roumbas, and Moussiopoulos (2004) conducted a life cycle evaluation on two hydrogen production methods: the natural gas steam reforming and the water electrolysis via renewable energy sources. Similarly, Cetinkaya, Dincer, and Naterer (2012) compared five hydrogen production methods: the steam reforming of natural gas, the water electrolysis by wind and solar energy, the coal gasification, and the thermochemical water splitting with a copper-chlorine (Cu-Cl) cycle. Pereira and Coelho (2013) performed a comparative LCA for the similar production methods under the European scenarios. Bhandari, Trudewind, and Zapp (2014) thoroughly reviewed 21 past research associated with life cycle studies of hydrogen production technologies. With no exception, those studies have pointed out the effectiveness of using renewable energy sources - wind, hydro and solar - to reduce emissions.

On the other hand, some other studies present the environmental impact for renewable energy sources in a different way. For example, Li, Yao, Tachega, Ahmed, and Ismaail (2021) rated Cu-Cl thermochemical water-splitting as the most environmentally friendly and sustainable technology among coal gasification, natural gas steam reforming, water electrolysis via wind power and Cu-Cl thermochemical water-splitting. Comparing steam reforming, biological methane reforming, and bioethanol-to-hydrogen systems, Noureddine Hajjaji, Pons, Renaudin, and Houas (2013) concluded that biomethane reforming systems was the optimistic.

LCA studies have also been performed to determine whether hydrogen is greener than other fuels. Granovskii, Dincer, and Rosen (2006) compared between a fuel cell vehicle and a gasoline one, concluding that fuel cell vehicles with hydrogen from natural gas would excel gasoline vehicles. They also introduced a new LCA method, called “the exergetic LCA” by adopting the exergy efficiency which could simplify the complexity of conventional LCA methodologies and contributed to drawing more explicit conclusions (Granovskii, Dincer, & Rosen, 2007). S. S. Hwang et al. (2020) conducted a comparative LCA which revealed the excellence of hydrogen as a marine fuel, compared to marine gas oil (MGO) and natural gas when applied for a 12,000-gross tonnage (GT) coastal ferry.

LCA on various types of fuel cells such as solid oxide fuel cell (SOFC) (Mehmeti, McPhail, Pumiglia, & Carlini, 2016) and molten carbonate fuel cell (MCFC) (Lunghi & Bove, 2003) have been also studied. de-Troya, Álvarez, Fernández-Garrido, and Carral (2016) evaluated the best conditions of fuel cell applications to ships. Multi-criteria decision making analysis (MCDA) was conducted by Inal and Deniz (2020) by considering eight criteria including environmental and economic aspects.

3.3. Identified research gap

This research has reviewed the current situation where LCA is widely applied, and how it is being applied in shipping. However, it is still difficult to give an answer to whether the marine alternative fuel and system discussed in this project are truly eco-friendly from the point of view of the life cycle. Numerous case studies of marine LCA discussed above cannot give general answer to this question, but also face many other problems and limitations.

As already mentioned, the first ISO LCA guidance is a generic approach but unable to provide details or pathway for specific case models. As a result, the discrepancy in modelling, processing and data collection have arisen across LCA studies (Guinee et al., 2010).

These questions led to several methodological developments, such as dynamic LCA (Pehnt, 2006; Su, Li, Zhu, & Lin, 2017; P. Wang, Li, & Kara, 2018), spatially differentiated LCA (Finnveden et al., 2009; Nitschelm, Aubin, Corson, Viaud, & Walter, 2016), risk-based LCA (Assies, 1998; Ayoub, Musharavati, Pokharel, & Gabbar, 2015) and hybrid LCA (Suh et al., 2004; Teh, Wiedmann, Castel, & de Burgh, 2017).

However, there are still innate limitations when the LCA is intent to be applied for decision making or regulatory frameworks. It is because that current LCAs were largely designed to indicate the environmental impact of case-specific studies with well-defined boundaries, not represent general trends or observations (Guinée, 2002; Rebitzer et al., 2004).

It is noted that despite several past LCA studies, none of them was able to offer practical insight into the underlying debate about whether maritime alternative fuels and systems such as scrubber systems, LNG, and hydrogen fuel cells are ultimately a clean energy source for marine applications. It is because those studies, as shown in Table C 2, were due largely conducted under case-by-case scenarios. Their results were technically correct under the corresponding conditions that they set, but they could not offer adequate suggestion for other cases in different research scopes, scenarios, regional characteristics, lifecycle models, assumptions, etc. In other words, those past research have been overly laden with the scenario-oriented analyses where some specific vessels were selected as ‘case ships’, and the flows of energy and emissions associated with shipping activities of those ships were tracked and evaluated. Those models were undoubtedly detailed for the given vessels but irrelevant to other ships.

The deep-seated limitations of the past research were a by-product of the conventional LCA procedures that was designed for case-specific analysis. As a result, it was inevitable to predict the overall trend on the basis of a few samples. Indeed, such an attempt was as absurd as predicting the behavior of tens of thousands of vessels from LCA results obtained on one or two vessels; it was even not known whether they were representative samples or merely arbitrary ones. It should be noted that the misuse of the outcomes of the past research may provide a false sense of confidence when inferring the performance of the whole fleets.

In order to minimize this gap, some researchers limitedly conducted the sensitivity analysis by comparing some credible scenarios to observe the deviations according to scenario changes (Blanco-Davis & Zhou, 2016; P Gilbert, Wilson, Walsh, & Hodgson, 2017; Jeong et al., 2018; Smol, Kowalski, Makara, & Henclik, 2019; H. Wang, Oguz, Jeong, & Zhou, 2018; H. Wang, Oguz, Jeong, & Zhou, 2019).

Some recent studies have started recognizing the problem and working on developing multiple scenarios to derive more general observation. For example, El-Houjeiri et al. (2019) conducted LCA considering LNG produced in various different regions such as Qatar, Australia, and U.S. Gulf Coast. Pavlenko et al. (2020) organized numerous case studies based in Qatar, U.S., Algeria, China, and Australia. In addition, Sharafian et al. (2019) compared domestic and imported LNG in various scenarios. There were also some comparisons among LNG propulsion systems which are ultra-steam turbine, four-stroke medium speed engine, and two-stroke low-speed engine systems onboard in terms of economic, environmental and technical performance of these systems (Jeong, Jang, Zhou, & Lee, 2019).

Nevertheless, their attempts could not address the fundamental limitations of LCA on a case-by-case basis, which are still far from providing us with generally applicable insights into the emission trends of all marine ships.

In view of this background, this project was motivated to develop LCA-based methodology, which can guide us to obtain general trends/insight of environmental impacts for all vessels. Therefore, those general results can be directly utilised for proper decision-making for future rule-making for marine environmental protection.

3.4. Concluding remarks

This chapter introduced a brief background and standardized process of LCA. However, the current policy evaluations used for eco-friendly evaluation do not reflect the LCA point of view in policies.

Meanwhile, LCA, which is increasingly used for environmental evaluation in various fields, is reflected in the same trend in the shipping sector as well. The current shipping industry is continuously developing and introducing more eco-friendly fuels and systems than HFOs to mitigation climate crisis and environmental pollution. However, it is not only limited by the inherent limitations of LCA, but also environmental evaluation studies for new alternative future marine fuels and systems are still lacking. In addition, methodologies and studies that can reflect the LCA concept in general policies while satisfying various stakeholders have not been conducted. Therefore, an enhanced methodology that can overcome these limitations is required to achieve the goal of this project.

4. METHODOLOGY

4.1. Introduction

In the previous chapter, the introduction of LCA, research trends, and research gaps were identified. Therefore, in this chapter, the parametric trend life cycle assessment (PT-LCA) developed to fill the research gap of existing research and overcome the limitations of conventional LCA was introduced. The section 4.4. presents the comparison between conventional LCA and PT-LCA showing specific differences between the two methodologies.

4.2. Parametric Trend LCA (PT-LCA)

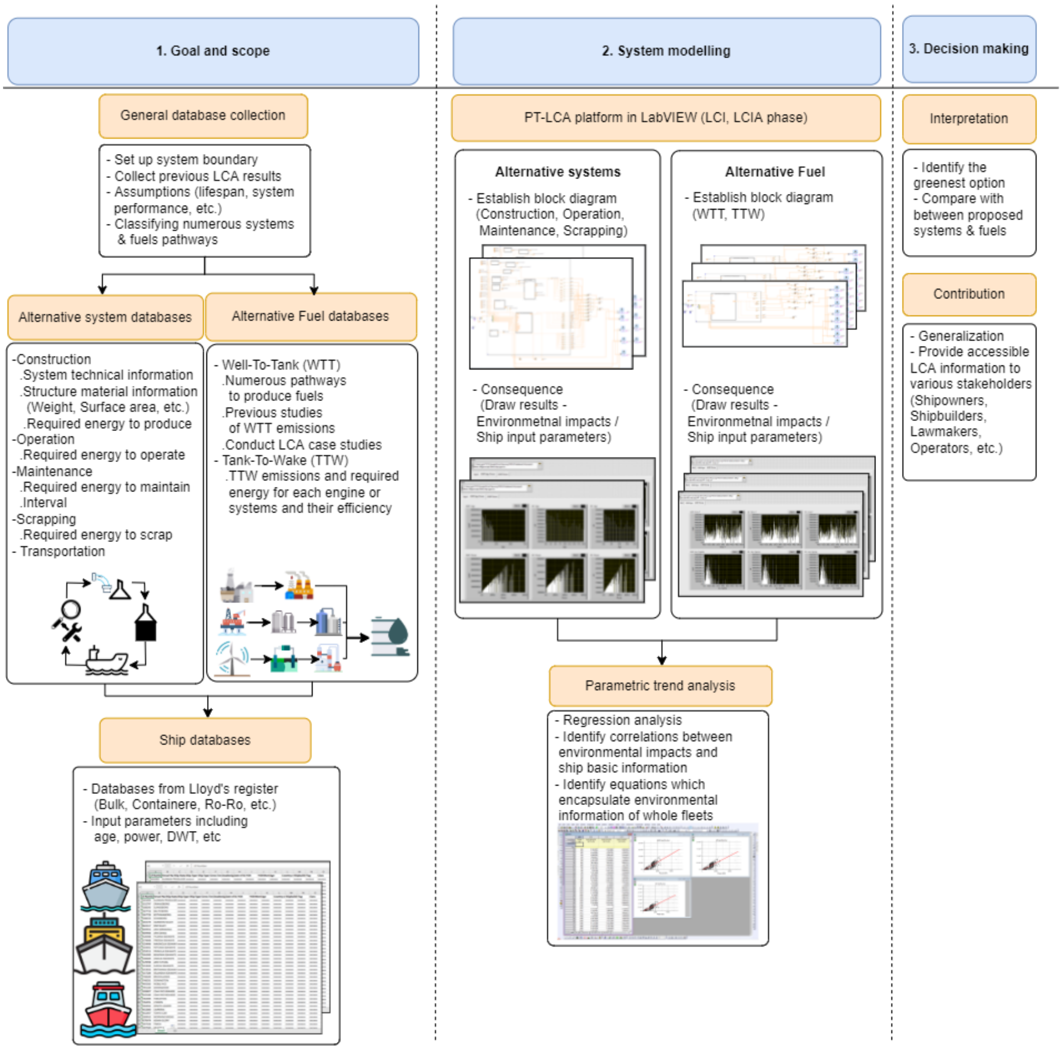

Figure 4-1: Schematic representation of a generic parametric trend life cycle assessment (PT-LCA).

Figure 4-1 shows the general process of the proposed LCA approach (defined as *Parametric Trend LCA* or *PT-LCA*), which consists of three steps. The first two steps are on the same line as the ISO guidelines but tailored for the purpose of this research, whereas the parametric trend analysis has been added to this enhanced LCA-based methodology. The process of the parametric trend analysis repeats the LCA process by inputting various parameters that will affect the results. For example, if the object of analysis is scrubber systems, the parameters in the dataset will be the specification information of various actual ships such as engine power, age, dead weight, etc. Finally, all the results from individual calculation are plotted into a single graph. The general trend displayed on the graph enables us to identify the correlation between each input parameter and emission levels.

While the conventional LCA is a steady-state methodology, it is relevant to point out that it is possible to save a lot of time and effort as a dynamic approach, which was constrained in terms of time and space (Guinee et al., 2010). In the end, a variety of decision-makers would be provided much broader holistic view with more information. Below is an explanation of how to proceed with PT-LCA shown in Figure 4-1.

4.3. Methods adopted for environmental assessment

4.3.1. Step 1. Goal and scope

(a) General database collection

In PT-LCA, the first step basically needs to set the system boundary and assumptions the same as in conventional LCA. For example, the fuel and system to be studied, the technical performance range, and the lifespan of the system are determined. However, since the PT-LCA covers thousands of case studies, the data coverage is much larger and more diverse than conventional LCA. In addition, once the overall boundary and scope of the study are established, the details that need to be collected will vary depending on whether the research object is a system or a fuel. Specifically, the research subjects covered in this project could be divided into fuel and system, and alternative systems and alternative fuels are implemented with different frameworks. The alternative system consists of construction, operation, maintenance, and scrapping, and the alternative fuel consists of Well-To-Tank (WTT) and Tank-To-Wake (TTW) phases.

(b) Alternative fuel & system databases

In alternative system LCA framework, system technical information or material information required for each step should be collected. In this process, the consumed energy and emission data are essential. Meanwhile, in alternative fuel LCA framework, WTT classifies numerous pathways required for each fuel to be produced, and information related to the amount of fuel, energy, and emission required for each pathway is essential. TTW needs to identify the emission values and efficiencies resulting from the use of these fuels on ships.

(c) Ship databases

Whereas the existing LCA selects a few ships and analyzes the environmental impact assessment for those ships from a life cycle perspective, PT-LCA selects all thousands of ships and performs LCA at the same time, so entire fleet of ship databases including various parameters such as age, power, DWT, etc. are essential. The collected database of thousands of ships is linked with the general database and alternative fuels and systems database collected in the previous step.

4.3.2. Step 2. Modelling

In this step, it is necessary to build a unique PT-LCA platform capable of performing LCI and LCIA based on the collected database of thousands of ships. To facilitate this, the 'LabVIEW' platform is implemented. LabVIEW, a visual programming language developed by National Instruments, is designed to be easier to use by providing excellent GUI features and graphics and provides excellent features for integrating thousands of data.

By inserting data into the platform, it calculates the total fuel consumption over the whole lifespan of the vessel. Once the total fuel consumption is calculated, it is possible to estimate the environmental impact. The LabVIEW platform is a tool that can calculate this process iteratively thousands of times simultaneously, with thousands of results graphed with the x-axis of the ship's power and the y-axis of environmental impacts such as GWP, AP, and EP.

For example, through this platform, the stages of production and consumption of hydrogen, LNG, diesel, etc. can be modeled by connecting a database of thousands of ships, and the environmental impact results according to the age, power, and DWT of each ship can be graphed. Once key activities in each stage are modelled, the types and quantities of emissions pertinent to each life stage of systems are to be estimated. The purpose of such modelling is to track the emissions produced by all activities, such as material production, transportation, and onboard usage. Therefore, it will measure emission values such as CO_2, SOx, and NOx for LCI phase, GWP, AP, and EP for LCIA phase. In this part, PT-LCA will be able to more easily handle the numerous input parameters composed of the collected database compared to the software 'GaBi' that conventional LCA would normally utilize.

In addition, the functional unit is set differently from the conventional LCA. While the existing LCA study is to evaluate the environmental friendliness of the goal, the PT-LCA is more focused on how the environmental impact changes according to the input parameters to help decision makers and rule makers. Basic information such as the age, power, and DWT of the ship are designated as input values in the modelling platform, and environmental impacts such as GWP, AP, and EP are the outcomes. For this reason, in the conventional LCA, it is difficult to achieve the goal pursued by PT-LCA because functional units are normally designated as simple units such as kg/kWh for comparative analysis and applied to actual ships. On the other hand, in PT-LCA, the correlation between input and output values can take over the role of traditional functional units. This correlation can be expressed as a condensed equation by displaying all results of individual LCA calculations in a single graph. For example, when the input value is the power of a ship, the environmental impacts such as GWP, AP and EP can be immediately figured out in terms of life cycle without complicated calculations with the power of the ship. As a result, we can predict the overall environmental impacts for all ships and compare with all ships regardless of power. The following is a more detailed explanation of how to implement and operate PT-LCA through Labview software in the system and fuel.

(a) PT-LCA platform in LabVIEW (LCI, LCIA phase)

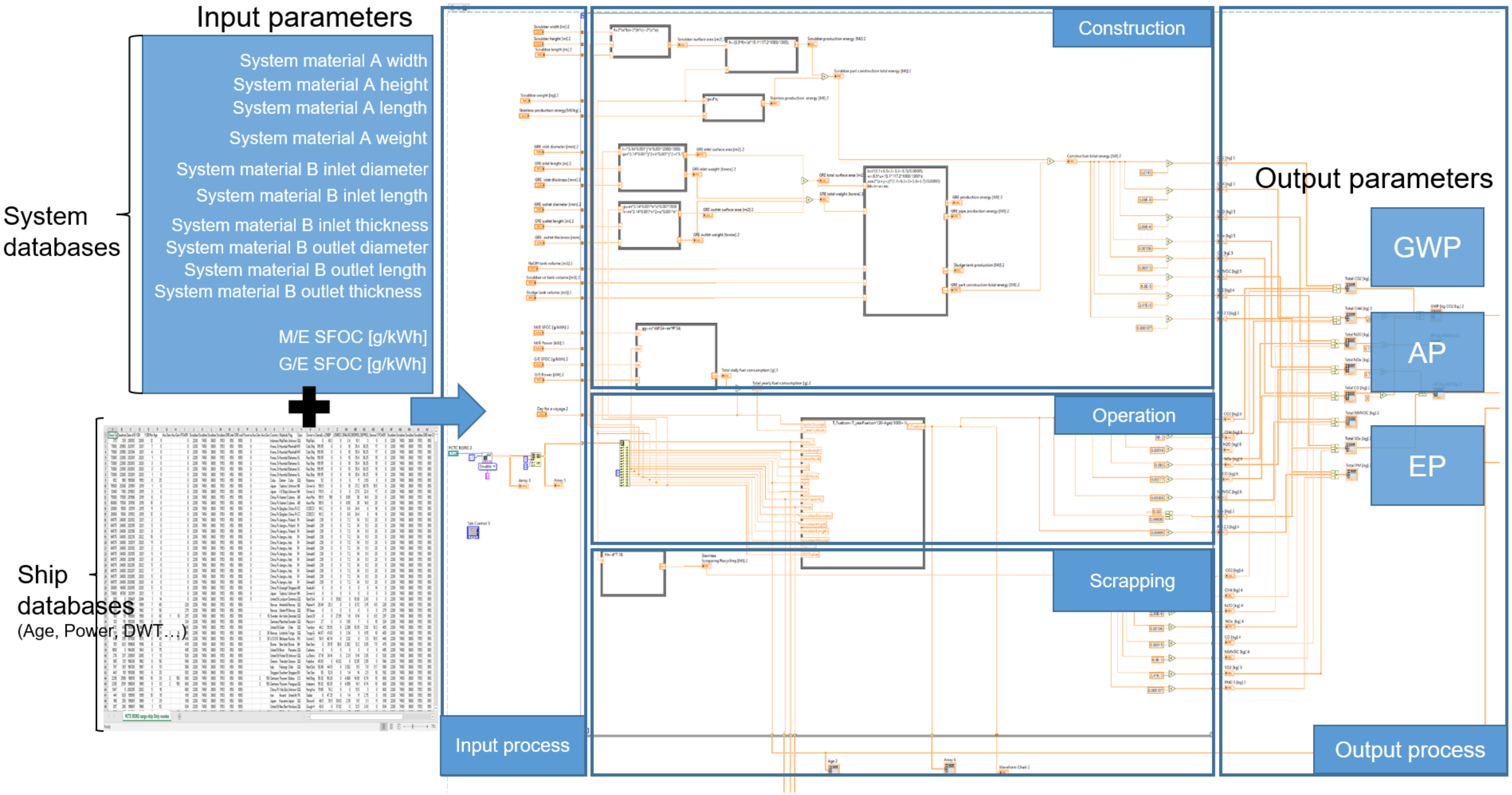

Figure 4-2: PT-LCA LabVIEW platform calculation procedure for a system

Figure 4-2 shows how to implement PT-LCA in LabVIEW. Specifically, Figure 4-2 presents that when modeling the alternative system in PT-LCA, each life cycle stage which are construction, operation, maintenance, and scrapping is implemented by integrating the data collected in the step 1. System parameters such as the surface area, weight, and volume of the materials constituting the system and vessel parameters are input parameters to the configured PT-LCA platform. Based on this database, the energy consumed for constructing and scrapping the system can be estimated. When the amount of energy consumed is calculated, the environmental impacts can be estimated. For example, when the material constituting the system is steel, the electrical energy consumed for cutting and welding the steel is 8.5 MJ/m^2 and 15.1 MJ/m, respectively (P Gilbert et al., 2017). Thus, the equation of electricity consumption of a system in which steel is a material as follows:

- $EC = 8.5 \times SA + 15.1 \times 117.2 \times TW \times 1000/1300$ [MJ]

Where,

EC: Electricity consumption

SA: Surface area [MJ/m2]

TW: Total weight [kg]

The operation electricity consumption will be calculated depending on how much the system consume electricity and the length of operation period. Estimated electricity consumption is simultaneously linked to a database of thousands of ships. In the end, it is derived from the thousands of environmental impacts produced when using the system in a database of thousands of ships.

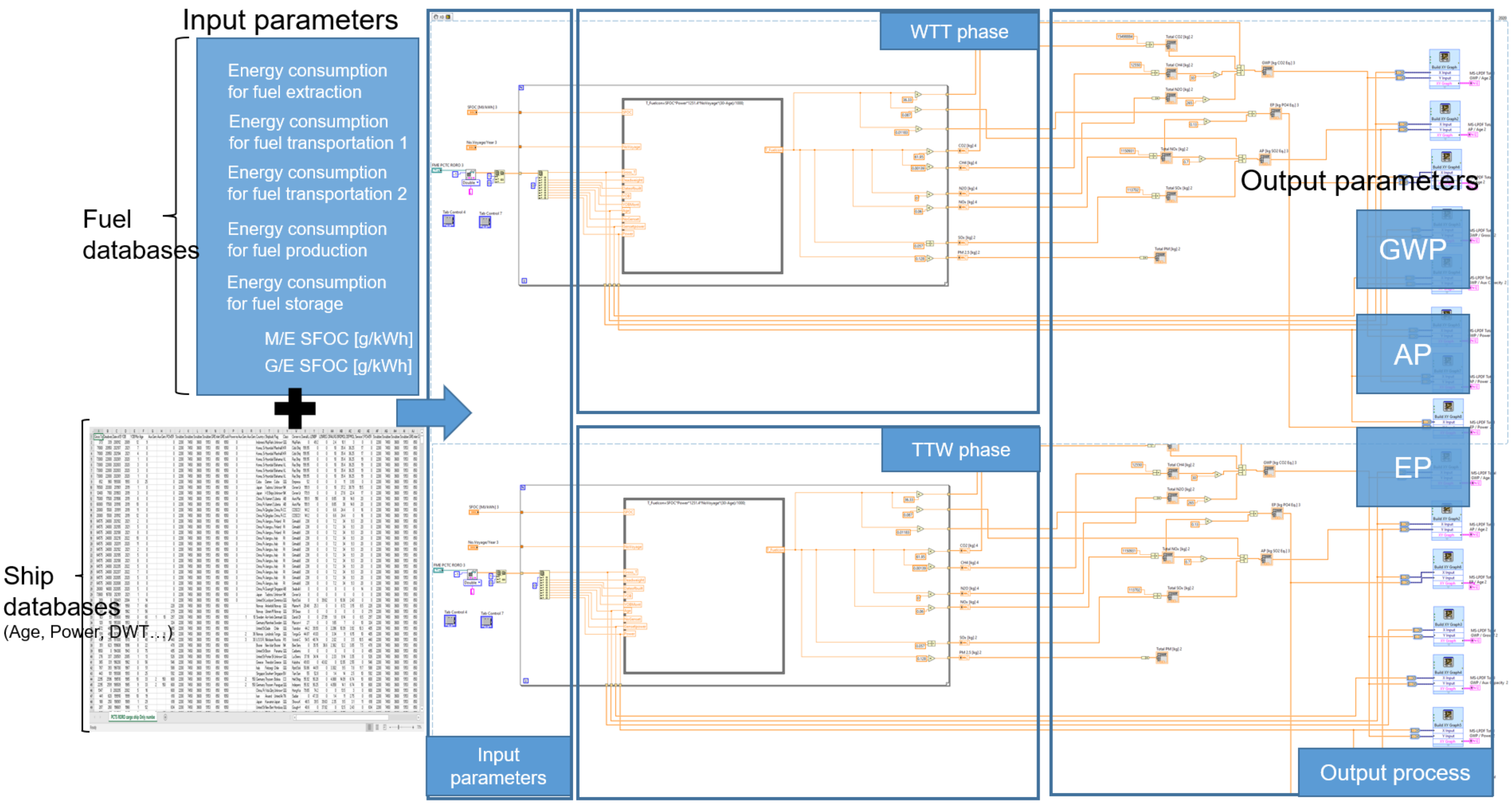

Figure 4-3: PT-LCA LabVIEW platform calculation procedure for a fuel

Figure 4-3 illustrates that PT-LCA is designed with WTT and TTW life cycle phases when modeling the alternative fuel. By inputting data from thousands of ships collected in step 1 into each LabVIEW platform, it iteratively calculates LCI and LCIA while calculating environmental emissions.

For WTT, fuel input parameters are energy consumed to extract the fuel and energy consumed for transportation and storage as well as engine SFOC. For TTW, fuel will be consumed during the entire lifespan of a vessel. Specifically, total fuel oil consumption can be calculated based on the information corresponding to each fuel pathway, the power of ship and specific fuel oil consumption (SFOC), and the total operating time of the ship. In addition, the lifespan of the vessel, existing WTT environmental impacts inventory databases and characterization factors should be collected in that process. Thus, thousands of environmental impact results such as GWP, AP and EP are output parameters through calculations obtained by substituting numerous input parameters into the total fuel consumption equation.

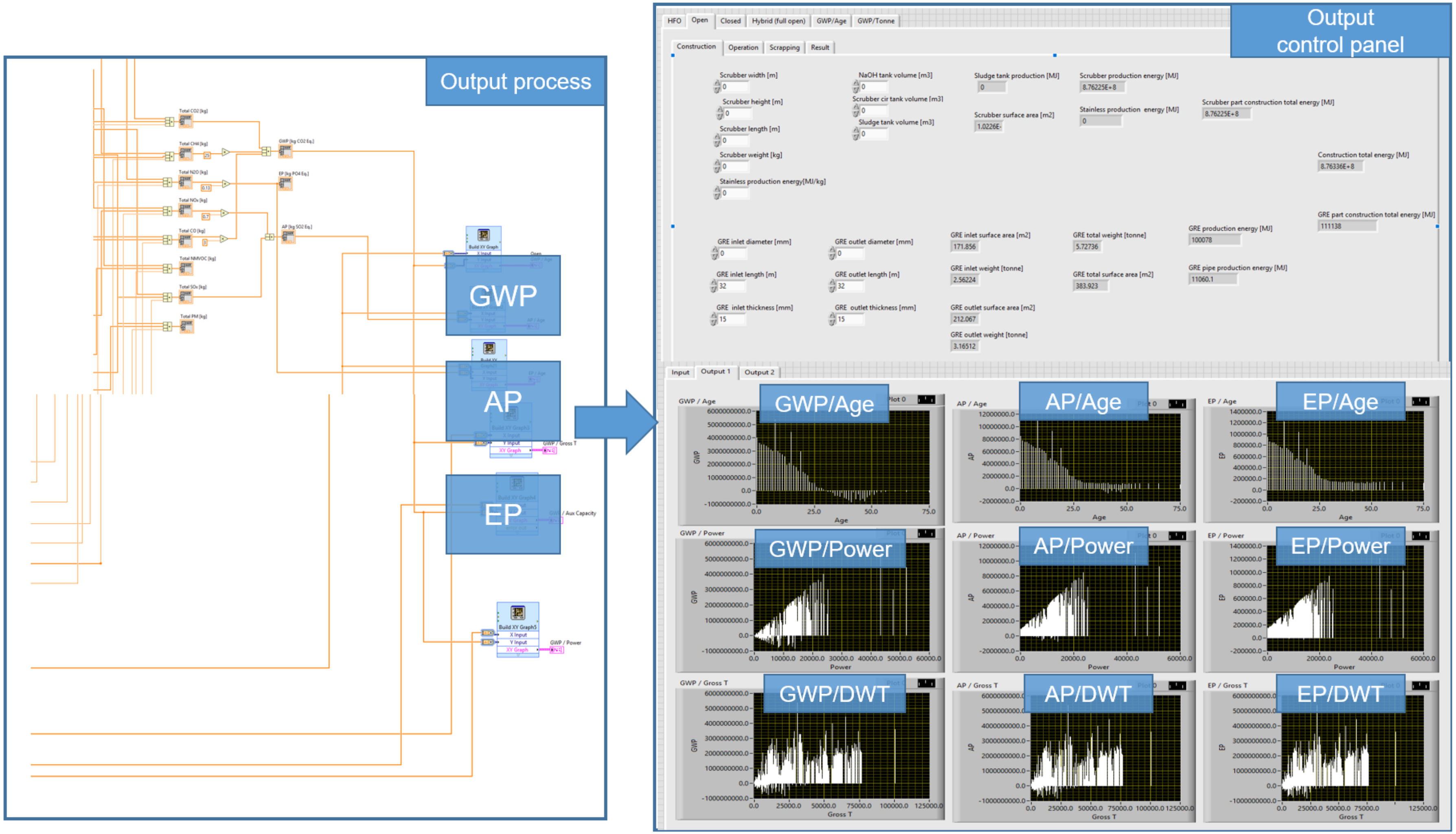

Figure 4-4: PT-LCA LabVIEW platform for graphed outputs

As shown in Figure 4-4, thousands of data calculated here are graphed and output as environmental impact values according to the basic information of each ship.

The environmental impacts such as GWP, AP, and EP derived from the PT-LCA platform are displayed on the output control panel as graphs according to the basic ship information age, power, and DWT. After all, it is possible to find out how the environmental impact value of the ship changes according to ship basic parameters.

(b) Parametric trend analysis

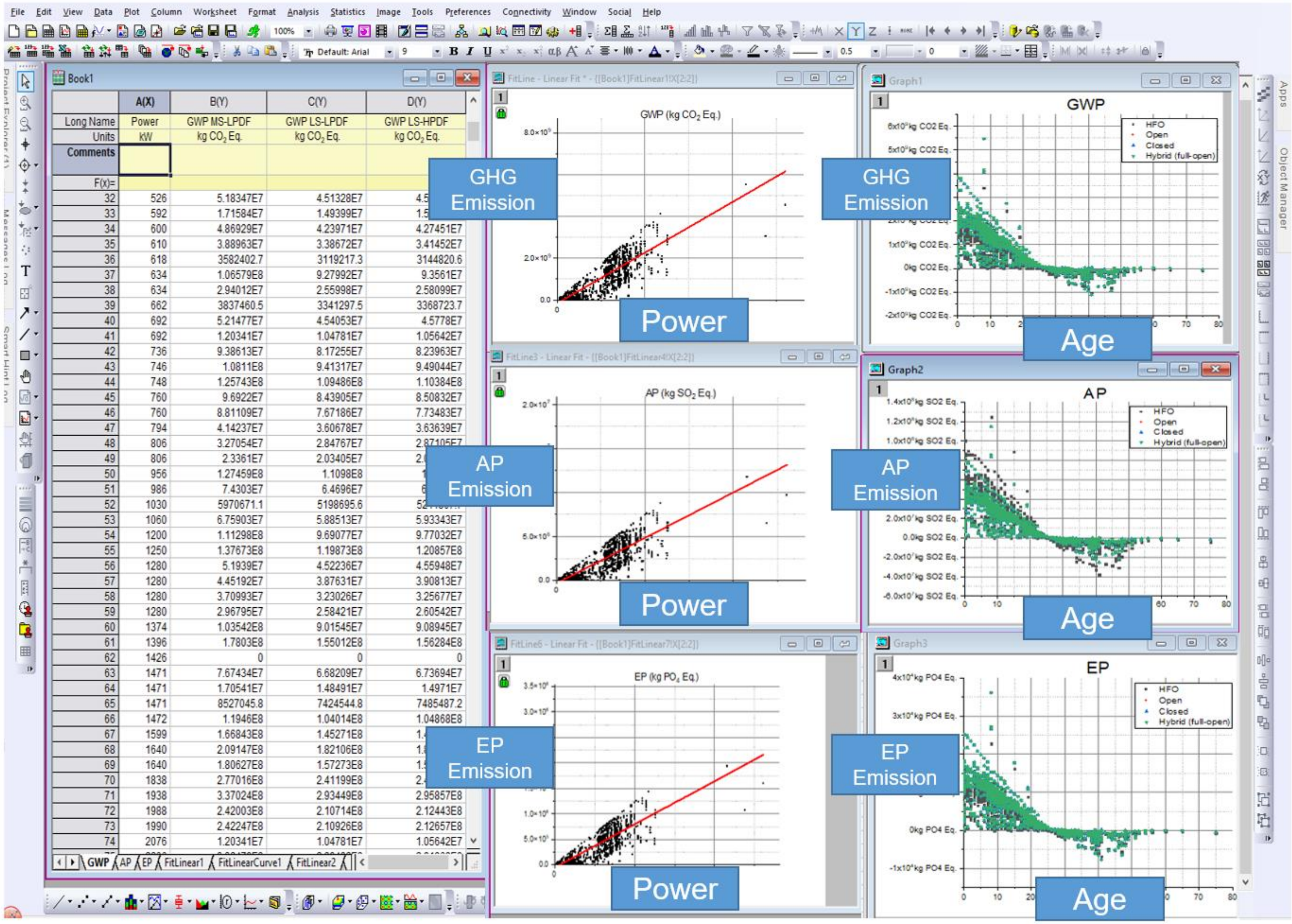

Figure 4-5: Linear regression process through origin screenshot.

Parametric trend analysis can be regarded as a generalisation process. It is because the individual results generated from repeatable LCA processes are consolidated to represent a general trend which can offer insight into the relationship between cleaning systems and mother ships in terms of environmental benefits. To be specific, Figure 4-5 shows that this stage is to check the correlation between the basic information of ship and environmental impacts, and the graphs derived through the two-stage modelling process are derived as an integrated trend line by linear regression.

For example, since thousands of ship data with various environmental impact factors are displayed as dots on the graph, the trend line derived by performing regression analysis using these dots can be converted into a linear equation form such as $y = a + bx$. This formula enables to infer how much environmental impacts change according to the power of the ship from the viewpoint of the life cycle.

Thus, many stakeholders would be able to find out the ship's LCA result easily and quickly with only the ship's basic information, saving time and economic loss. In addition, the derived equation can contribute to rational decision-making in implementing a ship environmental policy that affects the entire fleet.

For the verification of this tool, it may be required to conduct additional sensitivity or uncertainty analysis. However, Since PT-LCA was performed with the previously reviewed LCA results, sensitivity or uncertainty about data or model has already been verified. In addition, the purpose of this study is not to derive simple LCA results of a certain scenario to determine its accuracy or completeness, but to derive trends by understanding the correlation between basic ship information and environmental impacts through the LCA results of the entire fleet. Therefore, uncertainty analysis or sensitivity analysis for verification, it is considered unnecessary to perform additionally.

4.3.3. Step 3. Decision making

(a) Interpretation

The interpretation step is to interact with other steps over the whole process reflecting the ISO guideline. Therefore, it is required to check whether step 1 to step 3 are progressing harmoniously and consistently. This process is mainly focused on the whole processes, data usage and lifecycle modes and evaluation methods are consistent with the original goal and scope that may vary according to interested groups such as ship-owners, lawmakers and operators engaged in the marine sector. Above all, this step identifies the greenest fuels and systems interpreting the final results and also compares with numerous objectives.

(b) Contribution

By generalizing the conclusions drawn from parametric and trend analysis, various stakeholders (shipowners, shipbuilders, lawmakers, operators) can easily and quickly access the LCA environment evaluation results of the vessel even if they are not familiar with environment-related information. For lawmakers, for example, the developed methodology can provide a rationale for regulating the environment of ships. Shipowners or shipbuilders can immediately determine the environmental friendliness of the ships they own. Operators can operate by understanding the eco-friendliness of the vessel on board.

4.4. Comparison between conventional LCA and PT-LCA

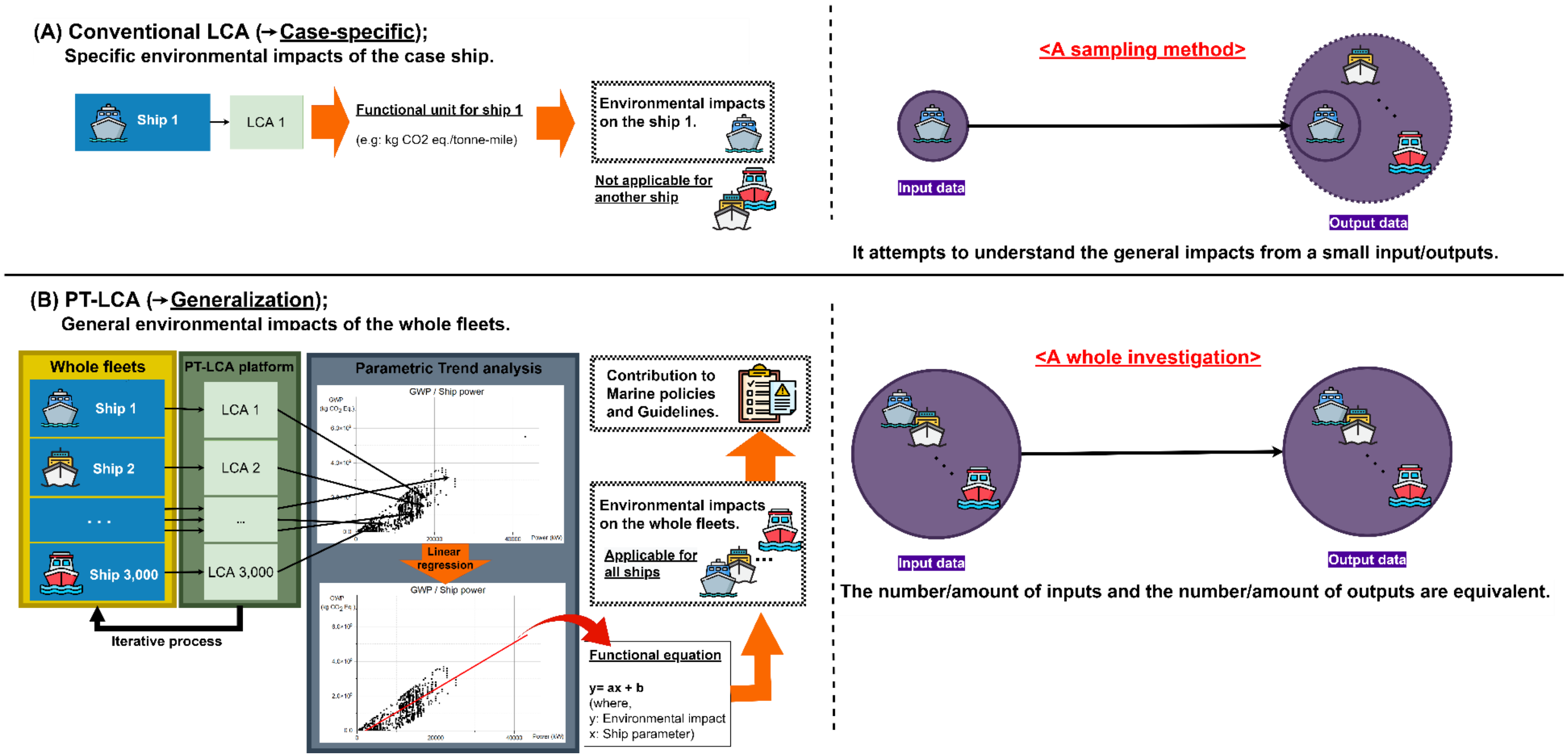

Figure 4-6. Comparison between conventional LCA(A) and PT-LCA(B).

Figure 4-6 shows the comparison between conventional LCA and PT-LCA. In the shipping industry, conventional LCA research have mainly conducted case studies by selecting one or two case ships. However, as revealed in literature reviews, these research results have inherent limitations that they cannot be applied to other case ships. This limitation causes time and economic loss when repeatedly performing LCA for numerous ships, and it leads to a problem that since it is too specific result only for few sample case studies, it cannot be adopted in maritime environmental policies or guidelines for thousands of ships. Meanwhile, PT-LCA was basically designed based on the ISO guidelines, but it uses thousands of data for the entire fleet rather than a single data for one or two case ships. In addition, as the parametric trend analysis process is added, it is significantly different from the conventional LCA in that the ultimate goal is to reflect the international policy through general observation by inferring the tendency of the LCA results of the entire fleet, not just one single LCA result. In this step, the input value was set as the ship's power and the result value was set as environmental impacts (GWP, AP, EP), so that it can be understood how much the environmental impact factors change from the life cycle perspective according to the power of a ship. Therefore, the conventional LCA derives only the specific LCA result of a specific vessel, but the PT-LCA derives the general LCA results of thousands of vessels.

5. PARAMETRIC TREND LIFE CYCLE ASSESSMENT FOR SCRUBBER SYSTEMS

5.1. Introduction

In this chapter, the PT-LCA was applied to scrubber systems, one of the alternative marine fuels and systems, to confirm the effect of PT-LCA and to determine whether there is any correlation between ship basic information (age, power, DWT) and environmental impacts (GWP, AP, EP). Additionally, while the scrubber systems market has grown extensively in temporary transport for HFO use, little is known about whether they are environmentally friendly from an LCA perspective. Therefore, eco-friendliness was analyzed through the PT-LCA in this chapter.

5.2. Goal and scope

5.2.1. Goal of the study

The primary goal of this chapter is to demonstrate the effectiveness of the PT-LCA by evaluating the life cycle environmental benefits of marine scrubber systems over the conventional heavy fuel oil (HFO) on 1,565 ocean-going Ro-Ro vessels. It is to determine the most environmentally friendly system across all scrubber systems. Finally, potential emission levels pertinent to different scrubber systems are to be estimated in accordance with various ships.

5.2.2. Application of Scrubber systems

Scrubber systems are a representative end-of-pipe technology that complies with upcoming regulations. As such, the scrubber system can be technically categorized into two types: 'wet scrubber' and 'dry scrubber'. Furthermore, the wet scrubber can be again divided into three operating types: 'open-loop', 'closed-loop' and 'hybrid'.

As of 2018, the open-loop scrubber systems account for about 64% in the marine scrubber market due to its simplicity and low capital costs; those scrubber systems are designed to directly spray sea water through the exhaust gas so that the natural alkalinity of sea water can neutralize acid contained in the gas (DNV, 2018). On the other hand, the closed-loop scrubber systems (about 4%) are operated by chemical-controlled fresh water with Sodium Hydroxide (NaOH) as the cleaning solution. This solution is not directly discharged to the overboard. Instead, it is neutralized in the process tank with NaOH and becomes reusable. Thus, the discharge of contaminated wash water can be considerably reduced, compared to open-loop scrubber systems. The hybrid scrubber systems (about 28%) are equipped with both open-loop and the closed-loop system functions (Register, 2012). Dry scrubber systems generally use $Ca(OH)_2$ as a reducing agent supplied to the system in the form of solid particles. However, due to high space requirements and costs, few dry scrubbers have been adopted in the marine industry

(Register, 2012). In this context, this research does not consider the dry scrubber systems.

For the wet scrubber systems, Figure 5-1 illustrates the system configurations and Table 5-1 presents the technical information.

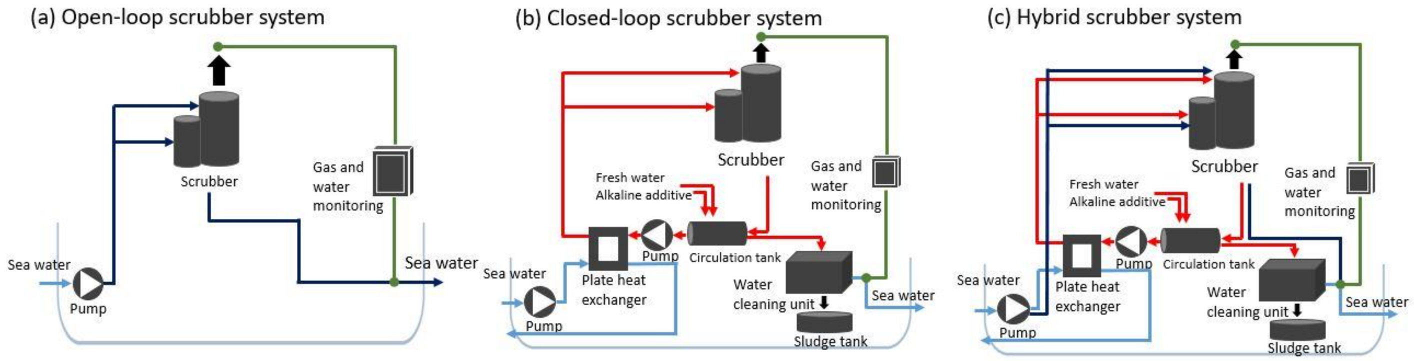

Figure 5-1: The configuration of proposed wet scrubber systems (ABS, 2017).

Table 5-1: Technical information for scrubber systems (ABS, 2017).

For engine size (MW)	5			25			50		
System	Open loop	Closed loop	Hybrid system	Open loop	Closed loop	Hybrid system	Open loop	Closed loop	Hybrid system
Performance	98% SOx removal								
Sources	Main engine (ME), auxiliary engine (AE) and boiler								
Size of Equipment (length × width × height)	3.9 × 2.2 × 6.4 m	3.8 × 2.1 × 6.6 m	3.9 × 2.2 × 6.4 m	8.6 × 5.0 × 11.0 m	8.2 × 4.6 × 10.8 m	8.6 × 5.0 × 11.0 m	12.1 × 7.0 × 14.3 m	11.6 × 6.5 × 14.0 m	12.1 × 7.0 × 14.3 m
Electricity consumption	59 kW	31 kW	59 kW/ 31 kW	296 kW	154 kW	296 kW/ 154 kW	593 kW	308 kW	593 kW/ 308 kW

To calculate the total emissions at the operation phase, the electricity consumption of each scrubber system is integrated with the total operating time of the case ship. The hybrid scrubber system can operate both modes (between open-loop and closed-loop) that can be switched according to voyage conditions.

Additionally, the size of sodium hydroxide tank, scrubber circulation tank and sludge tank required for closed-loop scrubber and hybrid scrubber were estimated to be 20, 15, and 20 m^3, respectively (Hansen et al., 2013).

5.2.3. General scope

The case study falls into two analyses: 1) the comparison of open-loop scrubber system with HFO, 2) the comparison among all credible scrubber systems.

(a) Case 1: HFO with open-loop scrubber system vs Ultra low sulphur fuel (ULSFO).

Case 1 was designed to respond to the fundamental question on whether the shipping industry can ultimately obtain environmental benefits from SOx scrubber systems when consistently using HFO as marine fuel. Figure 5-2 presents the life cycle process of the scrubber systems and the ULSFO within the scope of this analysis. Taking into account the dominant market share, the open-loop type was adopted for this analysis (DNV, 2018).

The LCA for ‘Scrubber systems’ represents the overall lifecycle process of the scrubber system consisting of construction, transportation, operation, maintenance, and scrapping. The additional electricity consumption to operate the scrubber system, thereby extra emissions from electricity generation are considered in the analysis.

In this context, the analysis scope of the HFO with open-loop scrubber system covers both LCA models of 'Scrubber system' and 'ULSFO' presented in Figure 5-2.

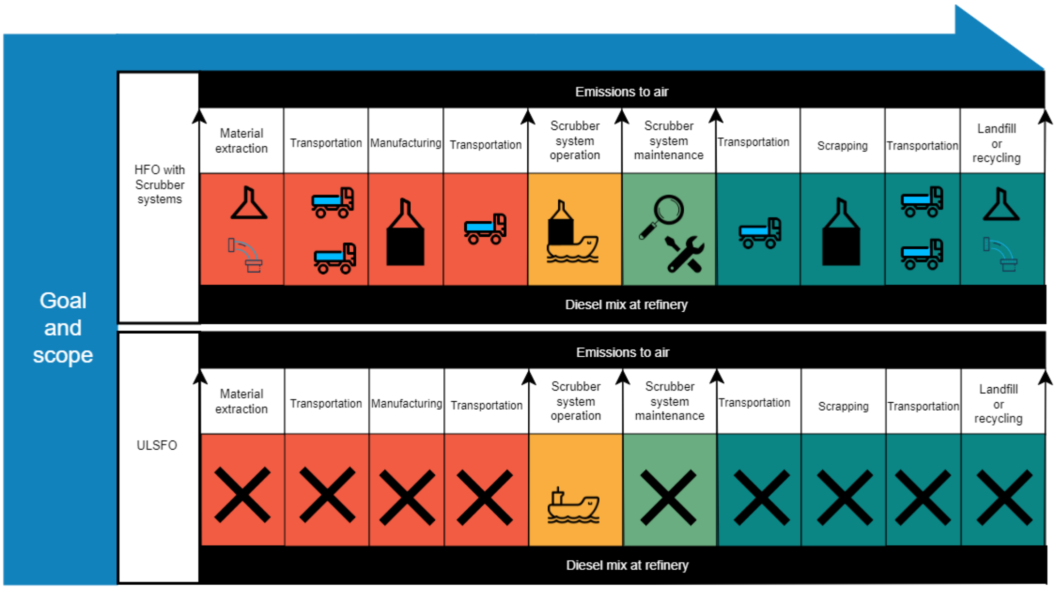

Figure 5-2: Outline of the LCA scope for scrubber systems in comparison with ULSFO.

(b) Case 2: Open-loop Vs Closed-loop Vs Hybrid

Given the purpose of Case 2 to evaluate the best solution of the three different types of scrubber systems, the scope of analysis is focused on the performance of scrubber systems. Therefore, the LCA scope of 'ULSFO' part given in Figure 5-2 is disregarded in this case.

The vessel data of 1,565 ocean-going Ro-Ro vessels (almost all Ro-Ro vessels subject to international regulations) was used for the analysis (*by courtesy of Lloyd's register*). Figure 5-3 illustrates the distribution of those vessels in accordance with ship age, engine power and gross tonnage.

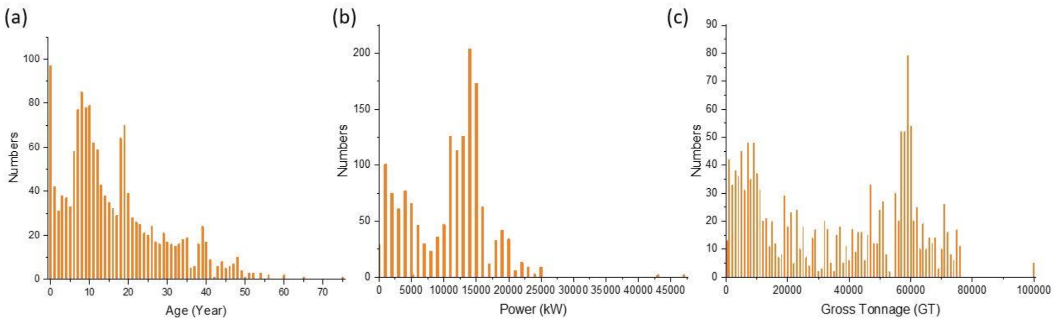

Figure 5-3: Distribution chart of the database source according to major input parameters: (a) vessel numbers according to age (Year), (b) vessel numbers according to power (kW) and (c) vessel numbers according to gross tonnage (GT).

Given this, three scrubber systems were applied to the whole case ships and the environmental performances of each system were investigated through PT-LCA.

5.3. Modelling

5.3.1. Construction phase

The construction phase refers to the life stage of the scrubber systems ranging from the raw material status to the onboard installation. The identification of the main materials of scrubber systems is one of the most crucial parts in this phase in order to calculate the energy consumption, thereby emissions, pertinent to the material productions. It was found that stainless steel for scrubber part and glass reinforced epoxy (GRE) for pipeline part would be commonly used (Register, 2012). In addition, the emissions corresponding to the transportation and the installation activities for the scrubber systems are taken into account.

The amount of each material used to manufacture scrubber systems was assumed based on the surface area and weight, while the level of energy consumption for material production was estimated based on the emission data for 'steel manufacture'. The energy consumption of manufacturing phase was estimated with the process data which guides 8.5 MJ / m2 of electricity for the cutting process and 15.1 MJ /m for the welding process (P Gilbert et al., 2017). The emission factors for unit electricity generation from diesel fuel are summarised in Table 5-2.

Table 5-2: Emission factors for 1 MJ energy production from diesel fuel (Elhami, Khanali, & Akram, 2017).

Emissions substance	CO_2	CH_4	N_2O	NO_x	CO	NMVOC	SO_2	PM
Amount (g/MJ diesel)	74.5	0.00308	0.00286	1.06	0.15	0.068	0.0241	0.107

5.3.2. Operation phase

The operation phase corresponds to the operational activities of the proposed scrubber systems over the ship lifetime. In this perspective, the underlying analysis for operation phase is to determine the energy consumption to operate those systems; the more energy consumption, the higher emission levels (H. Wang et al., 2018).

In principle, scrubber systems typically remove more than 97% of SOx emissions from engine exhaust gas (ABS, 2017). With reference to this point, the annual voyage was assumed to be 360 days at sailing. In terms of specific fuel oil consumptions (SFOCs), HFO for main engines and generator engines were assumed to be 172 g/kWh and 183 g/kWh respectively and ULSFO were assumed to be 167 g/kWh and 177 g/kWh (B Comer & Osipova, 2021; Kristensen, 2012; Turbo, 2014). The marine HFO and ULSFO emission factors, as shown in

Table 5-3, were used to calculate the emission levels from those engines.

Table 5-3: Emission factors for top-down emissions from combustion of fuels (Bilgili, 2021; IMO, 2014).

Emissions substance	HFO emissions factor (g/g fuel)	ULSFO emissions factor (g/g fuel)
CO_2	3.114	3.206
CH_4	0.00006	0.00006
N_2O	0.00015	0.00016
NO_x	0.0903	0.0961
CO	0.00277	0.00277
NMVOC	0.00308	0.00308
SO_2	0.053	0.002

5.3.3. Maintenance phase

The maintenance of scrubber systems is largely engaged with simple inspections such as pH level and spray nozzle which do not require any significant level of energy consumption or pollutants. Therefore, this phase was neglected due to its minimal environmental impact (AIR, 2016).

5.3.4. Scrapping phase

Lastly, the scrapping phase was assumed to be conducted in Bangladesh which is one of the most representative developing countries as well as India, Turkey and Pakistan due to low labour costs and weak environmental legislation (Abdullah, Mahboob, Banu, & Seker, 2013). The scrubber systems are mainly comprised of stainless steel which is more likely to be recycled rather than disposal (Rahman, Handler, & Mayer, 2016). The amount of emission generated by each electrical energy was estimated according to Table 5-4. The material of GRE was assumed to be disposed without extra energy consumption. Like construction phase, the electrical energy production emissions factors, as shown in Table 5-2, were used to quantify the emissions produced from electricity consumption.

Table 5-4: The summary of the energy consumed and emissions produced for recycling process (Moats, 2011).

Item			Stainless steel
Energy	MJ	Electricity	7.18
		Natural gas	2.6
Emission	Kg	SO_2	4.28E-04
		NO_x	5.27E-06
		CO_2	4.41E-01
		CO	1.01E-02
		$PM_{2.5}$	6.71E-02
		PM_{10}	8.46E-04

5.4. Results of analysis

For the sake of this case study, the key parameters to be considered would be the ship specification information such as engine power, age, dead weight, etc.; those factors contribute to determine the size and the lifespan of scrubber systems.

Finally, all the results from individual calculation are plotted into a single graph. The general trend displayed on the graph helps us to identify the correlation between each input parameter and emission levels. In this context, it can be said that the functional units for the PT-LCA are those correlations (formatted as equations) that can unswervingly represent the general trends or correlations over parametric changes as well as the total environmental impacts of target systems; this format of functional units are proposed to remedy the shortcomings of the common format of functional units (largely expressed as 'emission factors per unit energy consumption') that circuitously describes the environmental performance of scrubber systems through energy consumption basis

5.4.1. Results according to Age

(a) HFO with Open-loop scrubber Vs ULSFO

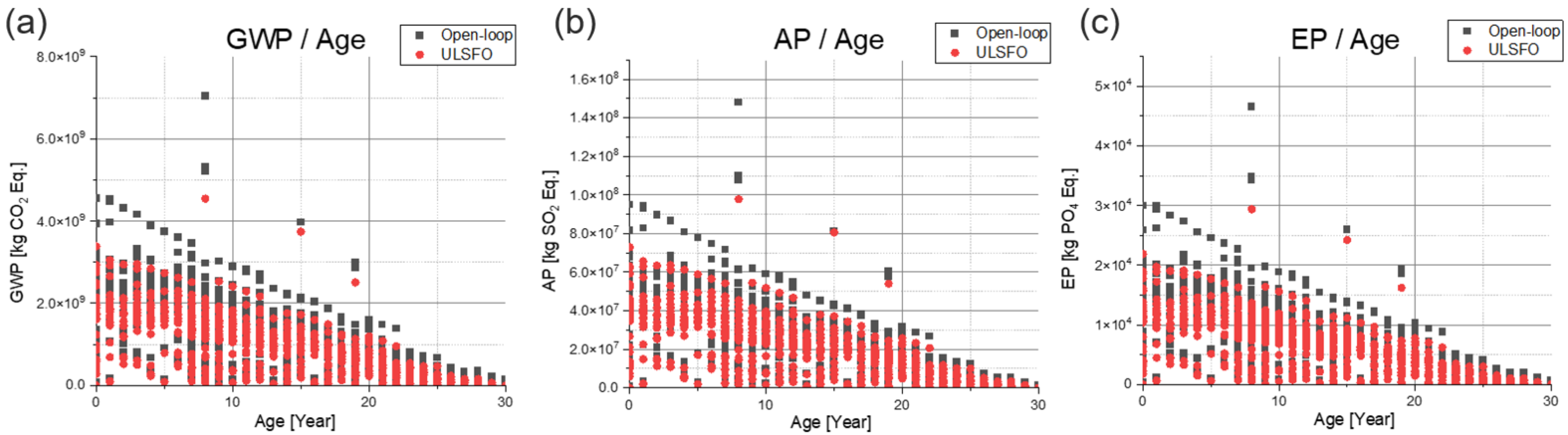

Figure 5-4: Results of parametric trend LCA for *HFO with open-loop scrubber systems* and *ULSFO* describing environmental impacts according to age [Year]: (a) GWP according to age (Year), (b) AP according to age (Year) and (c) EP according to age (Year).

Table 5-5: Total environmental impacts amount of *HFO with open-loop scrubber systems* and *ULSFO* when all individual ships adopt either way based on 1,341 Ro-Ro vessel samples.

	HFO with Open-loop	ULSFO only	Difference
GWP [kg CO_2 Eq.]	1.98E12	1.45E12	+36.5%
AP [kg SO_2 Eq.]	4.03E10	3.13E10	+28.7%
EP [kg PO_4 Eq.]	1.29E07	9.41E06	+37.1%

Figure 5-4 shows the analysis results of Case 1, indicating the environmental impacts of GWP, AP and EP over ship ages. The maximum life span of vessel was assumed 30 years and only 1,341 cases, younger than 30 years, were included among the total of 1,565 ships in the dataset. As illustrated in the figure, respective dots in graphs indicate the environmental impacts of individual case ships according to their ages. It clearly shows generally proportional correlation between environmental impacts and vessel age; the younger ships are more likely to produce more lifetime emissions due to longer scrubber system operation. On the other hand, it can infer that the reason why the same ship age has a wide range in GWP, AP and EP is due to different ship size, power, and other parameters. Their sensitivities on the environmental performance of different scrubber systems will be further discussed with Case 2.

Results from Figure 5-4(a) reveal that the option of using *ULSFO* was noticeably lower in the GWP than the other option of using *HFO with the open-loop scrubber system*. Such a tendency can be observed more clearly in Table 5-5 where the environmental potentials for each ship was integrated into the total levels. That is 1.45E+12 kg CO_2 Eq. indicates the total GWP level with 1,341 vessels using *ULSFO* whereas 1.98E+12 kg CO_2 Eq. represents the same vessels but using *HFO with the open-loop scrubber system*, indicating 36.5 % increase in GWP.

Considering AP results in Figure 5-4(b), *HFO with the open-loop scrubber systems* and ULSFO were compared. Table 5-5 shows 3.13E+10 kg SO_2 Eq. for the 1,341 vessels using *ULSFO* whereas 4.03E+10 kg SO_2 Eq. for the same vessels using *HFO with open-loop scrubber systems*. Hence, it was found that ULSFO could contribute more to reducing 28.7 % of AP from the whole fleet rather than open-loop scrubber systems. This fact reflects that the capability of open-loop scrubber systems is lower than that of using ULSFO, and from an AP reduction point of view, it shows that ULSFO can be a more attractive option than open-loop scrubber.

In addition, SOx scrubber manufacturers often advertise a 97% reduction in SOx emissions during operation (ABS, 2017). However, this research has shown that the actual effects of scrubber systems would be averaged at 28.7% higher than ULSFO in terms of whole life cycle perspective. It means that the life cycle processes and activities pertinent to scrubber systems have contributed significantly to emissions.

A trend similar to that of Figure 5-4(a) can be observed in EP results plotted in Figure 5-4(c); the *ULSFO* was lower in EP than the *HFO with the open-loop scrubber systems*. The total EP for the whole fleet for the *ULSFO* was estimated at 9.41E+06 kg PO_4 Eq., whereas the ships using *HFO with open-loop scrubber systems* was 1.29E+07 kg PO_4 Eq. (37.1 % increment in EP).

Study results deliver a crucial message regarding the application of scrubber systems for marine vessels. Although scrubber systems were proven excellent in removing SOx, it was found that the green shipping goal to reduce AP might cannot be achievable if the scrubber systems are not able to eliminate the other emissions - particularly, NOx and HCI - that negatively affect AP.

(b) Open-loop scrubber Vs Closed-loop scrubber

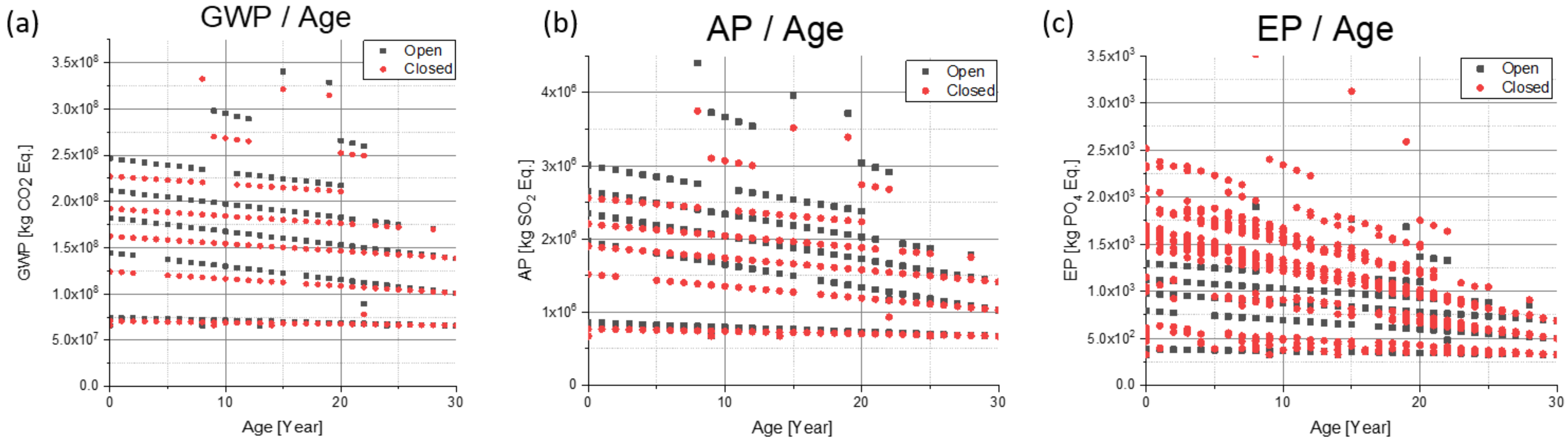

Figure 5-5: Results of parametric trend LCA for maritime SOx scrubber systems describing environmental impacts according to age [Year]: (a) GWP according to age (Year), (b) AP according to age (Year) and (c) EP according to age (Year).

Table 5-6: Total amounts environmental impacts of maritime SOx scrubber systems when all individual ships adopt either way based on 1,341 Ro-Ro vessel samples.

	Open-loop	Closed-loop	Difference
GWP [kg CO_2 Eq.]	2.13E11	2.00E11	-6.10 %
AP [kg SO_2 Eq.]	2.54E09	2.22E09	-12.6 %
EP [kg PO_4 Eq.]	1.11E06	1.61E06	+45 %

Although analysis results of Case 1 have raised questions on the environmental efficiency of the scrubber systems, there still needs to discuss the best options among different types of scrubbers in order to maximize the benefits through proper selection. The same number of ships under 30 years old was applied to this comparative analysis (Case 2).

In Figure 5-5(a), closed-loop scrubber systems were shown more eco-friendlier in GWP than open-loop scrubber systems and a similar tendency for the AP was observed in Figure 5-5(b). The results of EP described in Figure 5-5(c) are in contrast to the other two potentials. Open-loop scrubber systems had smaller EP relative to closed-loop scrubber systems. The energy consumption of the open-loop scrubber system is relatively less than that of the closed-loop system, which contributes to reducing the lifetime GWP and AP. On the other hand, the sludge produced in the cleaning process of the closed-loop scrubber had a negative effect on the results of EP.

It should be also noted that the environmental assessment results were spread out and fitted into largely six layers from left to right in all Figure 5-5. These layers have been formed due to the varying capacities of scrubber systems related to the engine sizes. These findings confirm that the main factors for the environmental impact of the scrubber system are the system capacity and the ship age.

The hybrid scrubber systems can be expressed as a combination of the open-loop and the closed-loop systems. It means that if this hybrid system only runs in the open-loop mode over the lifetime, the environmental impacts of this hybrid system at the operation phase are surely equal to the results of the open-loop system. The same is true for the closed-loop mode.

In other words, the operating times of each mode are regarded the key parameter to determine the environmental impacts of the hybrid systems. However, it is also clear that the boundary of these impact levels is to be placed within the maximum and the minimum impacts of the two systems.

5.4.2. Results according to Power

(a) Open-loop scrubber & Closed-loop scrubber

Using various ship powers as input parameters, a parametric trend analysis was performed to identify the general relations between the emission impacts and the ship power.

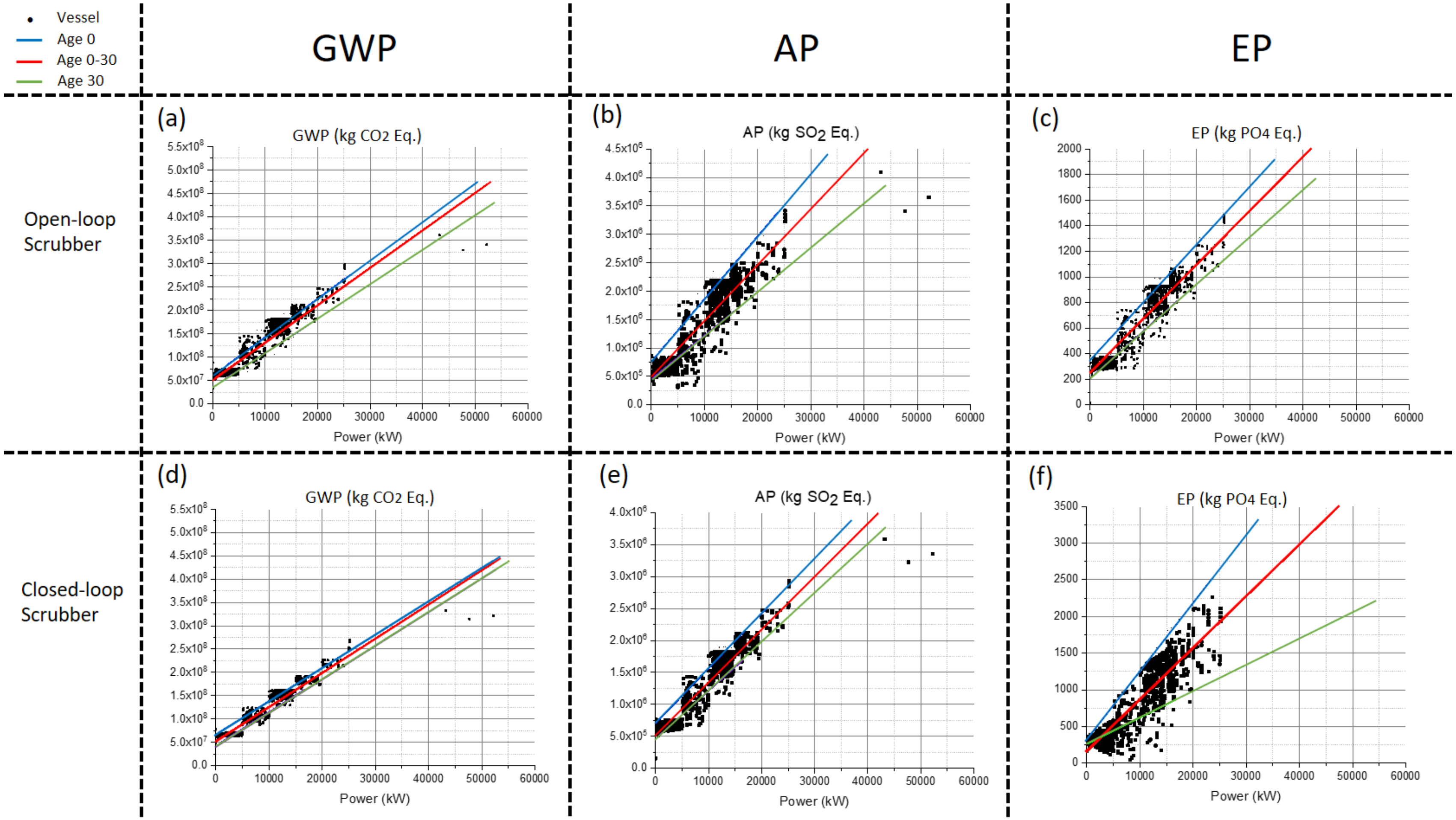

Figure 5-6: Results of PT-LCA for maritime SOx scrubber systems describing GWP, AP and EP according to power (kW): (a) GWP of open-loop scrubber systems according to power (kW), (b) AP of open-loop scrubber systems according to power (kW), (c) EP of open-loop scrubber systems according to power (kW), (d) GWP of closed-loop scrubber systems according to power (kW), (e) AP of closed-loop scrubber systems according to power (kW), (f) EP of closed-loop scrubber systems according to power (kW). (Blue line: regression values for vessels with age 0, Red line: regression values for vessels with age 0-30 group, Green line: regression values for vessels with age 30 group)

Table 5-7: Correlation based on the results of PT-LCA for maritime SOx scrubber systems describing GWP, AP and EP according to power [kW].

	Equation	Residual Sum of Squares	Pearson's r	R-Square (COD)	Adj. R-Square
(a) $y =$ GWP x = Power	Age 0: $y = 8236 \times x + 6.8E7$ Age 0-30: $y = 7989 \times x + 5.1E7$ Age 30: $y = 7326 \times x + 4.7E7$	1.8E16 4.2E17 3.9E15	0.98001 0.94848 0.94416	0.96041 0.89962 0.89143	0.96012 0.89955 0.88833
(b) $y =$ AP x = Power	Age 0: $y = 110 \times x + 7.8E5$ Age 0-30: $y = 98 \times x + 4.9E5$ Age 30: $y = 77 \times x + 4.8E5$	5.4E12 1.1E14 4.3E11	0.96735 0.91169 0.94397	0.93577 0.83118 0.89107	0.9353 0.83107 0.88796
(c) $y =$ EP x = Power	Age 0: $y = 0.04 \times x + 352.2$ Age 0-30: $y = 0.04 \times x + 250.4$ Age 30: $y = 0.036 \times x + 232.9$	6.4E5 1.4E7 9.7E4	0.97625 0.93739 0.94412	0.95307 0.87869 0.89136	0.95273 0.87861 0.88826
(d) $y =$ GWP x = Power	Age 0: $y = 7200 \times x + 6.5E7$ Age 0-30: $y = 7314 \times x + 5.3E7$ Age 30: $y = 7237 \times x + 4.7E7$	1.1E16 2.6E17 3.8E15	0.98387 0.9606 0.94421	0.968 0.92276 0.89153	0.96776 0.92271 0.88843
(e) $y =$ AP x = Power	Age 0: $y = 86 \times x + 7.1E5$ Age 0-30: $y = 83 \times x + 5.2E5$ Age 30: $y = 75 \times x + 4.8E5$	2.1E12 4.8E13 4.1E11	0.9792 0.94576 0.94416	0.95884 0.89446 0.89145	0.95854 0.89439 0.88835
(f) $y =$ EP x = Power	Age 0: $y = 0.09 \times x + 328.9$ Age 0-30: $y = 0.07 \times x + 155.2$ Age 30: $y = 0.03 \times x + 231.4$	3.4E5 7.9E7 9.3E4	0.99708 0.88813 0.95288	0.99418 0.78878 0.90797	0.99413 0.78864 0.90535

Figure 5-6 shows the proportional relationship between the ship power and environmental impacts which are GWP, AP and EP. As discussed earlier, as results of different ship characteristics (possibly various ship ages), the environmental impacts over ship power were somewhat scattered.

In order to interpret the emission-power relationship, the regression analysis was carried out: The blue line indicates the minimum with 0 year ships; the green line represents the maximum impact with the ships of 30 years; the red line represents the average impact on all concerned vessels.

Based on these graphs, general trends formulate each of the linear functions in Table 5-7. Those regressions were combined into a single equation which enables us to estimate the environmental impacts of scrubber systems as a function of ship age and power.

- $EI_{i,j} = (UL_{i,j} - LL_{i,j}) \times (30-A) / 30 + LL_{i,j}$

Where,

$EI_{i,j}$: Environmental impact of i for j

$UL_{i,j}$: upper line of i for j (Blue line on the graph)

$LL_{i,j}$: Lower line of i for j: (Green line on the graph)

A: ship age

Subscript

i: environmental impact categories e.g. GWP, AP and EP.

j: scrubber system types e.g. open-loop and close-loop

This research output can straightforwardly advise that closed-loop scrubber is the most environmentally suitable for a shipowner who has a 10-year-old vessel with 20 MW power. This fact can be a considerably serviceable for establishing regulatory/decision-making guidelines.

(b) Hybrid scrubber

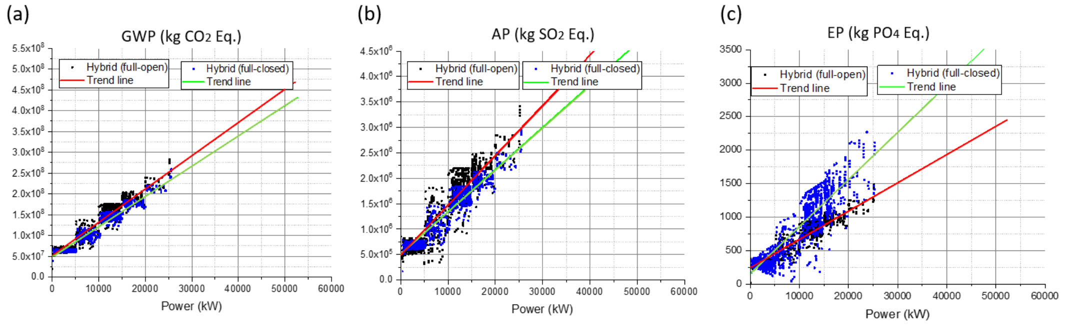

Figure 5-7: Results of PT-LCA for hybrid SOx scrubber systems describing environmental impacts according to power [kW]: (a) GWP according to power (kW), (b) AP according to power (kW) and (c) EP according to power (kW). (Red line: when hybrid scrubber has been fully operated open-loop system, Green line: when hybrid scrubber hs been fully closed-loop system).

As mentioned earlier, since the hybrid scrubber systems consist of the open-loop and the closed-loop systems, the operating times of each mode could significantly influence to determine the environmental impacts of the hybrid systems. Based on this fact, presented the environmental impacts of the both cases when it was fully operated by open-loop system and closed-loop system with red line and green line respectively. These two lines represent the maximum and the minimum value of each environmental impacts of hybrid scrubber system. Therefore, it could be figured out that since the hybrid system will have an environmental impact value between the red and green lines, the more closed-loop systems are used in GWP and AP, the more hybrid scrubber system is environmentally friendly. On the contrast, in the aspect of EP, the more open-loop systems are used, the eco-friendlier it is. Because of this opposite result regarding each environmental impact, as mentioned earlier, the impact between each environmental impact is likely to be addressed in future studies.

5.4.3. Results according to Gross tonnage

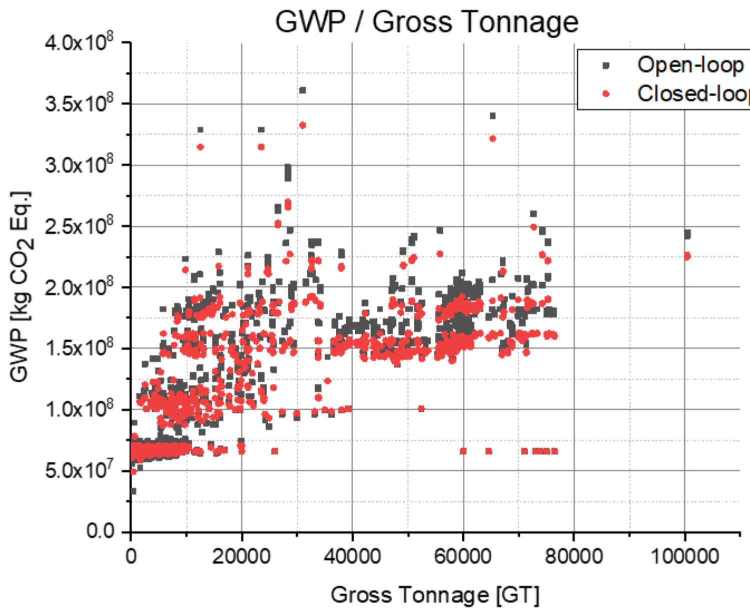

Figure 5-8: Results of parametric trend LCA for maritime SOx scrubber systems describing GWP according to Gross Tonnage [GT].

An additional parametric trend analysis was performed to investigate the relationship between emissions and other ship characteristics such as gross tonnage, dead weight tonnage, etc.

Figure 5-8 shows the GWP over various ship gross tonnages, but no clear correlation would be found. An increasing trend was observed across the tonnage, but it still seems irregular. The similar results were found in the other parameters of dead weight tonnage, ship length, etc; due to the lack of meaningful information, those results were persuaded not to be presented in this chapter.

Throughout a series of trial and error, it could be concluded that the two main parameters - ship power and age - are closely associated with the emission levels.

5.4.4. Comparative analysis with container vessels

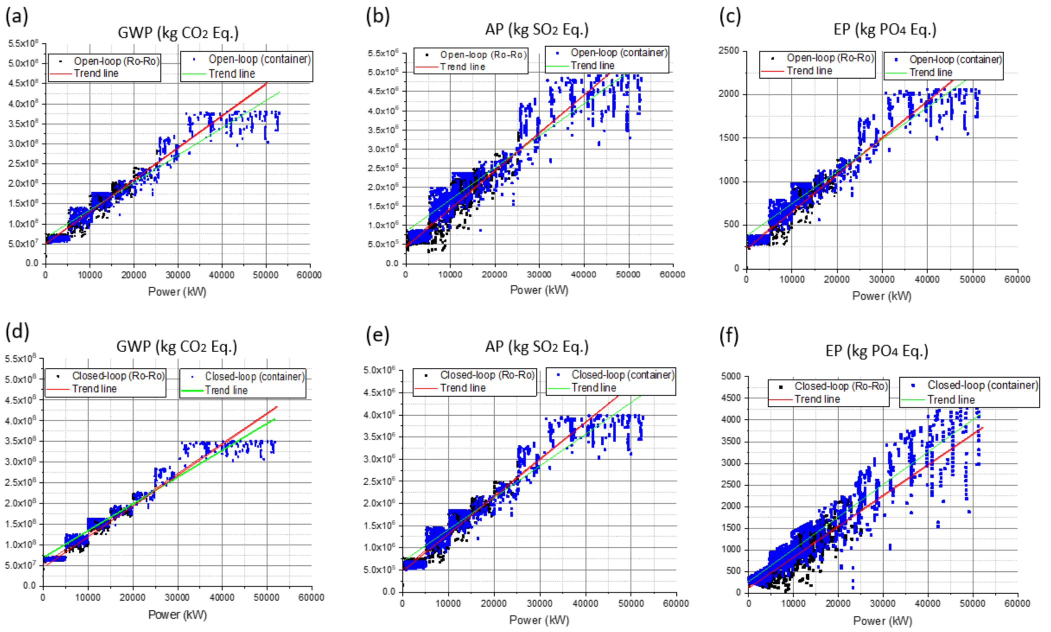

Figure 5-9: Results of PT-LCA for open-loop scrubber systems and closed-loop scrubber systems describing environmental impacts according to power [kW] with the 4,166 container vessels comparing to the results of Ro-Ro vessels: (a) GWP of open-loop system according to power (kW), (b) AP of open-loop system according to power (kW) and (c) EP of open-loop system according to power (kW), (d) GWP of closed-loop system according to power (kW) , (e) AP of closed-loop system according to power (kW) and (f) EP of closed-loop system according to power (kW) (Red line: results of Ro-Ro vessels, Green line: results of container vessels).

Figure 5-9 shows the comparative analysis between the results of PT-LCA for Ro-Ro vessels and 4,166 container vessels (by courtesy of Lloyd's register). Except for Figure 5-9(f), the results from Figure 5-9(a) to Figure 5-9(e) present that container vessels are more sensitive to environmental impact by power than Ro-Ro vessels. This could be one of the examples that PT-LCA is also possible to estimate the environmental impact of the subject systems in accordance with non-linear parameters such as ship types. Nevertheless, a prerequisite interpretation and re-formatting of those parameters is required to be suitable for PT-LCA platform. Those parts will be investigated in the future studies.

5.5. Concluding remarks

This chapter aimed to identify any correlation between ship basic information and environmental impacts and to evaluate the environmental impacts of the entire life cycle of three different SOx reduction scrubber systems: (1) 'wet open-loop', (2) 'wet closed-loop', and (3) 'wet hybrid'. A case study designed with the database consisting of 1,565 ocean-going Ro-Ro vessels based on Lloyd's Register has revealed that, in terms of Global Warming Potential (GWP) and Acidification Potential (AP), closed-loop scrubbers were proven more environmentally friendly than open-loop scrubbers, but the opposite was true for Eutrophication Potential (EP). By identifying specific trends in scrubber systems in relation to various input parameters, the assessment contributed to the total estimated amount of numerical environmental impacts that the scrubber systems have for the international fleets. The proposed LCA-based methodology enabled us not only to evaluate the different emission levels of systems applied to various ships but also to obtain the general trends of emission levels over ship parameters, which were expressed as formulae. The novelty of this chapter can be placed on the provision of an insight into the optimal selection of scrubber systems depending on ship characteristics. It could also offer an insight into the improvement of current environmental regulations and guidelines by means of PT-LCA.

6. PARAMETRIC TREND LIFE CYCLE ASSESSMENT FOR LNG FUELLED SHIPS

6.1. Introduction

This chapter adopts PT-LCA for LNG fuelled ships, which is currently in the spotlight after HFO as marine fuel. Chapter 5 revealed whether there is a correlation between basic ship information and environmental impact. In Chapter 6, PT-LCA was applied to LNG, which is currently receiving the most spotlight after HFO. Since LNG is a fuel that is increasingly controversial as to whether it is eco-friendly or not due to methane slip, the LCA of the entire ship was derived through PT-LCA, and general conclusions were drawn from various viewpoints.

In addition, based on the correlation between ship basic information and environmental impact revealed in Chapter 5, LNG LCA framework that can be easily and quickly applied to various stakeholders was developed and a baseline for establishing maritime policy and regulation was proposed.

Possibility of applying PT-LCA to fuel as well as system, and through comparison between ship types and engine types, the scope of the developed methodology has been expanded.

Figure 6-1 illustrates how the PT-LCA has been applied to predict the lifecycle environmental impacts associated with thousands of LNG fuelled vessels, assuming the use of LNG as marine fuel.

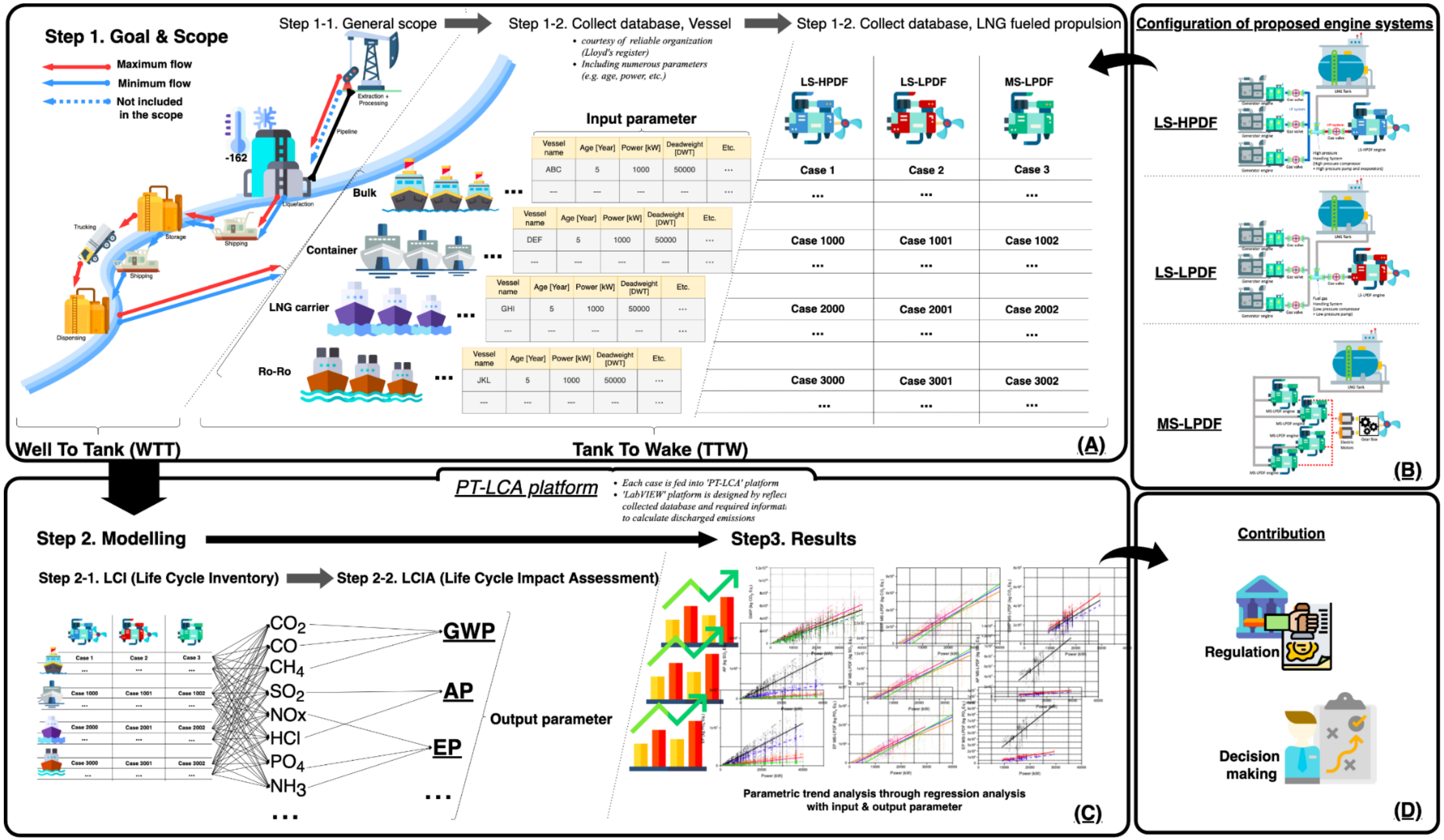

Figure 6-1: Flow diagram of LNG PT-LCA.

6.2. Goal and scope

6.2.1. General scope

This chapter profoundly deals with the holistic environmental impacts of using LNG as marine fuel from well to wake (from energy production to onboard use) as illustrated in Figure 6-1(A). The LNG life cycle can be broken into two parts: well-to-tank (WTT) and tank-to-wake (TTW). The WTT, often referred as upstream, represents the life stages from raw material extraction, LNG processing and supply chain to final arrival onboard. The TTW, or downstream, embodies the onboard use phase.

Table C 2 summarizes the LCA results obtained from previous LNG studies. The PT-LCA adopts the maximum and minimum paths as input parameters for WTT analysis to quantify the environmental impact of thousands of ships and observe the difference in results according to input sources.

The TTW analysis is coupled with marine database covering full ship specifications engaged in international services for the four most common ship types: bulk carriers, container ships, LNG carriers and Ro-Ro ships. Three representative marine LNG engines (Medium-speed low-pressure dual-fuel (MS-LPDF), Low-speed low-pressure dual-fuel (LS-LPDF) and Low-speed high-pressure dual-fuel (LS-HPDF)) are combined with the entire ship fleets, thereby estimating the correlations between ships and engines in terms of environmental potentials.

Regarding the scope and boundaries of this analysis, here are important points to be defined:

- The major emissions which are CO_2, CH_4, SO_x and NO_x are investigated based on primarily literature data.
- LCA models are only focused on the life cycle of LNG excluding emissions from life cycle of ships and LNG fueled propulsion systems.
- Four types of thousands of vessel databases are compiled from Lloyd’s Register.
- Lifespan of vessel is assumed to be 30 years without berthing or anchoring.

- LS-LPDF, LS-HPDF and MS-LPDF are chosen as the most representative LNG propulsion systems based on literature.
- LCA models consist of WTT and TTW, from production to LNG consumption onboard.
- Based on environmental inventory database derived from the maximum & minimum pathway databases, environmental impacts are calculated and applied to thousands of ships.
- The selective catalytic reduction (SCR) system for the LS-HPDF engine is assumed to reduce NOx emission by 95%.
- The functional unit for PT-LCA are represented as mathematic equations expressing correlations between ship basic information and environmental impacts.

6.2.2. Data collection

(a) Vessel

The four proposed ship types - bulk, container, LNG carrier and Ro-Ro – were recognized as having the greatest impact on marine air pollution (Lowell, Wang, & Lutsey, 2013). As such, the relevant information of the entire fleets in those ship categories were collected through the Lloyd's Register maritime database; it offers thousands of ship specifications including flag, age, power, DWT, etc. The number of ships falls into 2,009 for bulk carriers, 3,539 for container ships, 512 for LNG carriers and 1,254 for Ro-Ro ships. Figure 6-2 shows the general distributions that indicate the association between the number of vessels and specifications: ship age, power, and DWT.

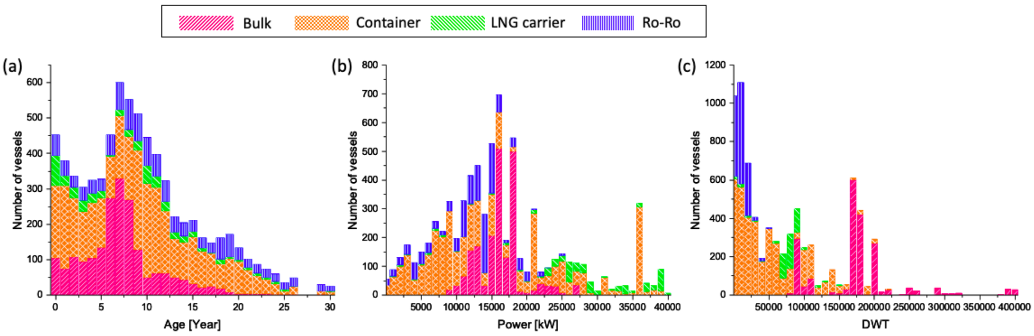

Figure 6-2: Distribution chart of the four types of vessels database according to major input parameters: (a) vessel numbers according to age (Year), (b) vessel numbers according to power (kW) and (c) vessel numbers according to deadweight (DWT).

The ships in the database are generally aged on a scale from 0 to 30 years, while ships between 4- and 11-years account for about 50% of the total vessels. Those vessels have wide ranges of engine powers, generally from 1,000 kW to 40,000 kW. Ships having power between 10,000 and 20,000 kW are more than 52% of the total. However, the power of LNG carrier ships is normally ranged between 23,000 and 40,000 kW. The number of vessels having less than 60,000 DWT accounts for about 53%, while bulk carriers are largely likely to have 80,000 DWT or greater.

(b) LNG fuelled propulsion

Hitching the rise above the growing LNG popularity as a cleaner marine energy source, several types of gas engines have been come into the market over the last two decades; such as steam turbines, LBSI engines, low-pressure injection dual-fuel (LPDF) engines, high-pressure injection dual-fuel (HPDF) engines and gas turbines (Pavlenko et al., 2020). As of today, the following three internal engine types dominate the shipping market: MS-LPDF, LS-LPDF, LS-HPDF (Pavlenko et al., 2020). In addition to this, Low-speed diesel cycle engines (LSD) using HFO are also considered as a reference in engine-to-engine comparisons.

Figure 6-1(B) shows the conceptual configuration of each engine type. For the MS-LPDF engines, four sets of engine systems are arranged in parallel so that the electricity generated from these engines converges into the common switchboard which distributes the combined electricity to the electric motor fitted with the propeller through the gear box (Fernández, Gómez, Gómez, & Insua, 2017). The MS-LPDF engines, which adopt Otto cycle with about 44% efficiency in general (Sharafian et al., 2019), can be maintained the compression ratio 5-6 bar lower than diesel cycle engines during combustion by mixing MGO as pilot fuel and natural gas (Pavlenko et al., 2020).

The LS-LPDF engines also adopt the Otto cycle with a similar combustion principle as the LS-MSDF engines. However, natural gas with higher pressure (about 10 bar) is injected to cylinder, which slightly improves the engine efficiency to about 51% (Sharafian et al., 2019). The engines produce mechanical power that is transmitted to the propellers.

The LS-HPDF engines work on a Diesel cycle in gas mode. Diesel cycle is operated at high temperature and pressure and longer time period, compared to Otto cycle (Noroozian, Sadaghiani, Ahmadi, & Bidi, 2017). Since the formation of NOx emissions, which comprise mainly NO and NO_2, are highly sensitive to the temperature and gas injection pressure in combustion chambers and the residence time of oxygen present, NO_x emission levels with Diesel cycle are normally greater than that with Otto cycle engines (ur Rahman et al., 2022).

Therefore, to comply with NO_x levels in MARPOL Annex VI, additional post-treatment such as exhaust gas recirculation (EGR) or selective catalytic reduction (SCR) should be installed (Sharafian et al., 2019), which can reduce NO_x by more than 95% by using NH_3 as a reducing agent (X. Liang, Zhao, Zhang, & Liu, 2019). Like LS-LPDF engines, the mechanical forces of the LS-HPDF engines are also produced and transmitted through shafting systems to the propeller.

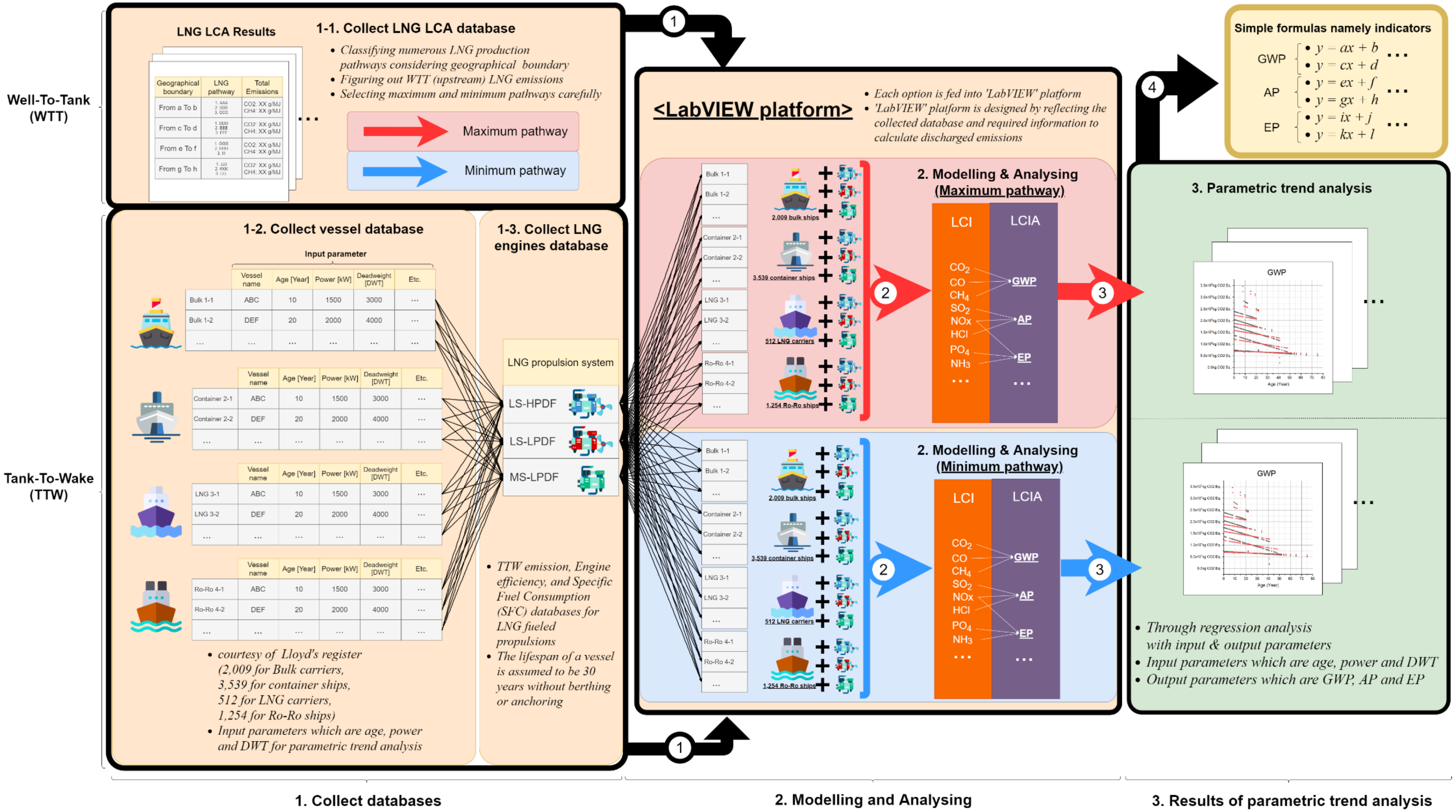

Figure 6-3: Flowchart on LNG PT-LCA Modelling process.

6.3. Modelling

In this chapter, vessel basic information such as age, power, tonnages, etc. from Lloyds' register would be corresponded as inputs, whereas environmental impacts, like GWP, AP and EP, are outputs as shown in Figure 6-3. The step 2 is all about the pathway to developing relevant LCA models to attain those correlations.

The model of life cycle inventory analysis (LCI) can be considered as a platform where inputs are processed to evaluate the quantities of emissions; representative emission types associated with marine engines are CO_2, CO, CH_4, HCl, NO_x, SO_x and NMVOC according to (IMO, 2014, 2018). The proposed LCI model couples the input parameters with the lifecycle emission factors predetermined through past LCA research, thereby completing the process of emission quantification that can be split into two stages: the WTT and the TTW.

6.3.1. LCI for Well-To-Tank (WTT) emissions

Since previous LCA studies on LNG fueled ships have their own purpose, and scope shown in Table C 2, the LCA results somewhat differ from each other. Such a gap suggests that the LCA rarely offers any single 'right' way in estimating emission factors. In this context, this study collected some WTT emission factors from two studies showing the results in most dissimilar ways: one represents the highest emission levels and the other represents the lowest as shown in Table 6-1. In this respect, it can be deduced that the emission levels of a particular LNG WTT analysis are likely to be placed within this gap.

Table 6-1: Maximum & Minimum pathways WTT inventory data.

Characteristic Units [g/MJ]	LNG		HFO
	Minimum pathway (Brynolf et al., 2014)	Maximum pathway (Sharafian et al., 2019)	(Sharafian et al., 2019)
CO_2	8.30×10^{0}	2.67×10^{1}	1.86×10^{1}
CH_4	3.30×10^{-2}	3.20×10^{-1}	1.60×10^{-1}
NOx	9.50×10^{-3}	9.10×10^{-2}	5.50×10^{-2}
NMVOC	6.90×10^{-4}	-	-
N_2O	1.70×10^{-4}	-	-
NH_3	7.70×10^{-7}	-	-
PM_{10}	3.20×10^{-4}	4.70×10^{-3}	7.90×10^{-3}
SO_2	8.30×10^{-4}	2.33×10^{-2}	3.40×10^{-2}

First, the maximum pathway covers the following life stages of LNG: extraction, pipeline supply, liquefaction, shipping, storage, trucking and dispensing. Meanwhile, the minimum pathway relatively considers those life stages: extraction, liquefaction, shipping, storage, shipping and dispensing. Finally, through both pathways, the LNG fuel proposes to be supplied to four types of vessels: bulk, container, LNG carrier and Ro-Ro carrier.

In Figure 6-1(A) of the WTT section, the red line refers to the maximum pathway of LNG, while the blue line shows the minimum pathway. The maximum pathway is assumed as the imported LNG scenario where the NG extracted from North America enters the LNG liquefaction stage after passing the 1,500 km pipeline as a nominal value. The cryogenic energy below - 162 °C is transported by ship to other countries, stored, and then distributed to consumers by truck.

On the other hand, the blue line represents minimum pathway of LNG. The minimum pathway is assumed to be extracted from Norway, and it goes directly to the liquefaction stage without the pipeline stage. The LNG is transported and stored in Gothenburg, then distributed by ship.

Table 6-2: Characterization factor for selected environmental impact categories.

Impact categories [Unit]	Characterization factors	Original reference
GWP [kg CO_2 Eq.]	1 CO_2, 30 CH_4, 265 N_2O	(Stocker et al., 2013)
AP [kg SO_2 Eq.]	1.88 NH_3, 0.7 NO_2, 1 SO_x	(van Oers, 2016)
EP [kg PO_4 Eq.]	1 PO_4, 0.35 NH_3, 0.022 COD, 013 NO_x	(van Oers, 2016)

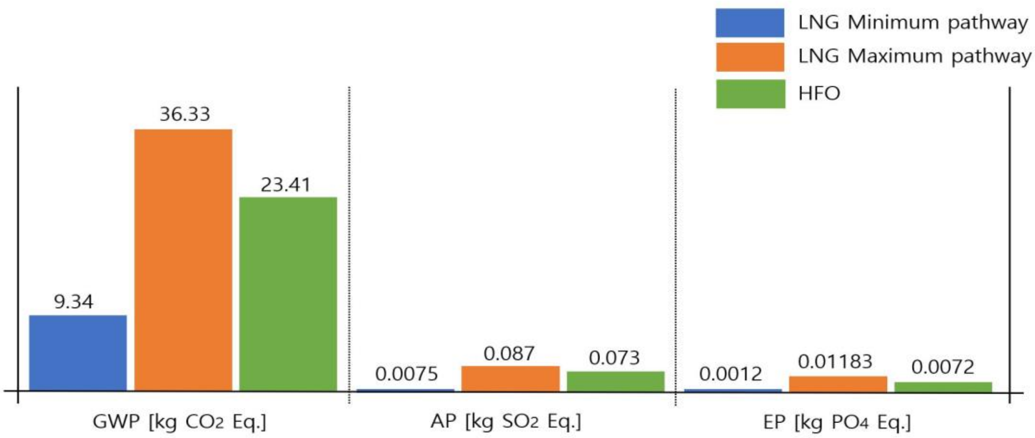

Figure 6-4: WTT Environmental impacts (Brynolf et al., 2014; Sharafian et al., 2019).

Using the data as input for the analysis in Table 6-1 and Table 6-2, the WTT environmental impacts were estimated as shown in Figure 6-4. In addition, given that the LS-HPDF engines still produce high levels of NO_x emissions, this engine type is generally required to be equipped with the aforementioned SCR system. For the case of LS-HPDF engines with SCR system, the WTT life cycle inventory database was offered in Table 6-3.

Table 6-3: WTT Life cycle inventory results of SCR entire system (Z. Liang, Ma, Lin, & Tang, 2011).

Emissions		Process		
		Production	Transportation	Installation
Atmospheric emissions (kg)	CO	7.67×10^4	4.76×10^1	-
	CO_2	9.58×10^6	1.84×10^4	1.00×10^6
	SO_x	6.65×10^4	3.29×10^1	8.00×10^3
	NO_x	3.05×10^4	6.81×10^1	5.00×10^3
	Hydrocarbon	1.32×10^3	-	-
	CH_4	1.26×10^4	-	-
	H_2S	6.06×10^1	-	-
	HCl	6.09×10^2	-	-
	HC	-	9.50×10^0	-
	NH_3	-	-	-

6.3.2. LCI for Tank-To-Wake (TTW) emissions

For the WTT, results of the LCA were somewhat inconsistent due to several factors such as different scenarios and input variables applied to the analysis. On the other hand, the TTW analysis could yield relatively consistent results by assuming each ship would be operated at design speed (maximum engine operating load) constantly at all time to understand the environmental impact of the worst case scenarios as shown in Table C 3 (Pavlenko et al., 2020).

Thereby, with the aforementioned assumption that the lifespan of vessel was assumed to be 30 years without berthing and anchoring, the total fuel consumption of each vessel could be calculated based on the specific fuel consumptions (SFC) and the engine efficiency.

In addition, for the case of LS-HPDF engines with SCR system, the NOx emission amount of LS-HPDF in Table C 3 was required to be adjusted from 1.22 g/MJ to 0.06 g/MJ and the TTW inventory database for the SCR was offered in Table 6-4.

Table 6-4: TTW Life cycle inventory results of SCR entire system (Z. Liang et al., 2011).

Emissions		Process
		Operation
Atmospheric emissions (kg)	CO	-
	CO_2	4.90×10^{6}
	SO_x	3.92×10^{4}
	NO_x	1.12×10^{6}
	Hydrocarbon	-
	CH_4	-
	H_2S	-
	HCl	-
	HC	-
	NH_3	2.20×10^{1}

6.4. Results of analysis

By applying thousands of cargo ships in the four different categories, the PT-LCA was conducted so that correlations between the inputs and the environmental potentials through regression analysis were determined as shown in Figure 6-3. The three main environmental impacts, namely GWP, AP and EP were considered to be evaluated as those potentials are most closely related to the maritime air pollution; the IMO has strengthened environmental regulations to gradually curb those emissions (Jang et al., 2020). Analysis results will be further discussed following sections.

6.4.1. Comparison of ship types

Figure 6-5 shows the overall trends of environmental impacts, referred to as well-to-wake (WTW), for the proposed ship types with engine power up to 40,000 kW. In general, it has been shown that the environmental impacts tend to ramp up with the rise in vessel power. Three thresholds have been identified that change the rank of ship types in terms of emission levels. To be specific, Figure 6-5 indicates three points with which it can be divided into four sections: 1) *'Before A' point*, 2) *'Between A & B' points*, 3) *'Between B & C' points,* and 4) *'after C' point.* For brevity, every single diagram is not subject to full discussion. Instead, some underlying points and findings are summarized as below:

'Before A' point (about 14,000 kW or less)

'Before A point' shows bulk carriers are ranked no. 1, presenting the greatest impacts on the environment. It is followed by container, Ro-Ro, and LNG carrier across all cases. In Figure 6-5(c), a bulk carrier with an engine power of 10,000 kW (LS-HPDF) emits more emissions than a container ship with the same engine type and power: 1.21×10^9 kg CO_2 Eq. and 1.08×10^9 kg CO_2 Eq. respectively. A Ro-Ro ship with the same condition follows with 1.01×10^9 kg CO_2 Eq. On the other hand, an LNG carrier with the LS-HPDF at 10,000 kW reveals much lower lifecycle GHG emissions compared to other ship types.

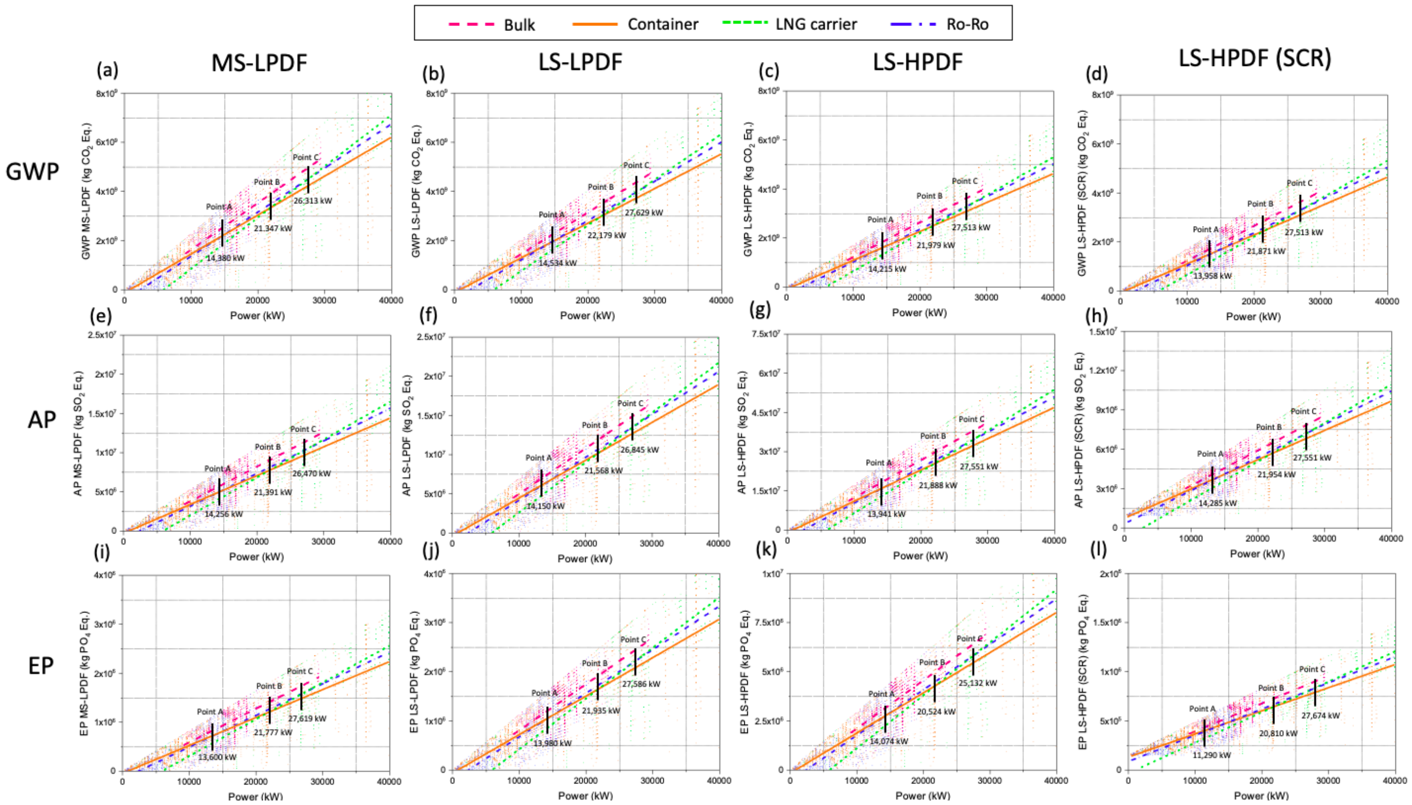

Figure 6-5: Results of comparison of vessel type through parametric trend LCA describing environmental impacts according to engine power [kW]: Lifespan of a ship is 30 years, WTW environmental impacts which are GWP, AP and EP trends for the four ship types (Bulk - Red dash line, Container - Orange solid line, LNG carrier - Green short dash line, Ro-Ro - Blue short dash dot line). (a) MS-LPDF, GWP according to ship power [kW], (b) LS-LPDF, GWP according to ship power [kW], (c) LS-HPDF, GWP according to ship power [kW], (d) LS-HPDF (SCR), GWP according to ship power [kW], (e) MS-LPDF, AP according to ship power [kW], (f) LS-LPDF, AP according to ship power [kW], (g) LS-HPDF carrier, AP according to ship power [kW], (h) LS-HPDF (SCR), AP according to ship power [kW], (i) MS-LPDF, EP according to ship power [kW], (j) LS-LPDF, EP according to ship power [kW], (k) LS-HPDF, EP according to ship power [kW], (l) LS-HPDF (SCR), EP according to ship power [kW].

Likewise, AP and EP also show similar trends. In Figure 6-5(g) and Figure 6-5(k), at 10,000kW engine output, a bulk carrier emits 1.24×10^7 kg SO_2 Eq., whereas a container carrier releases with 1.10×10^7 kg SO_2 Eq.. A Ro-Ro ship produces with 1.03×10^7 kg SO_2 Eq. and an LNG carrier is with 6.46×10^6 kg SO_2 Eq. The same trend is also found in the other engine types of LS-LPDF, MS-LPDF and LS-HPDF (SCR).

'Between A and B' points (approximately 14,000 to 21,000 kW)

In the section *between A and B*, the environmental impact of the Ro-Ro ship is observed to increase so that the ranking order is changed: bulk, Ro-Ro, container, and LNG carrier from high to low. In Figure 6-5(c), the difference between 2.26×10^9 kg CO_2 Eq. for a container ship and 2.35×10^9 kg CO_2 Eq. for a Ro-Ro ship is negligible. On the other hand, a bulk carrier at 20,000 kW contributes about 15% greater in GWPs than an LNG carrier at same power. Similar results are found for other local environmental potentials of AP and EP as well as for other engine systems such as LS-LPDF, MS-LPDF and LS-HPDF (SCR).

'Between B and C' points (about 21,000 to 27,000 kW)

In this section, the smallest differences in environmental impact are observed among ship types. Those impacts of LNG carriers tend to increase, and the ranking order changes to bulk, Ro-Ro, LNG carrier and container from high to low impacts. With the vessel power of 25,000kW, in Figure 6-5(c), a bulk carrier emits 3.34×10^9 kg CO_2 Eq. which is 14% higher than the emission level of 2.85×10^9 kg CO_2 Eq. from a container with the same power.

'After C' section (about 27,000 kW or greater)

With the continual increase in the environmental potentials, the LNG carriers outruns the Ro-Ro ships. As a result, the order turns out to be bulk, LNG carrier, Ro-Ro, and container. In Figure 6-5(c), at 35,000 kW, a bulk and a container emit 4.75×10^9 kg CO_2 Eq. and 4.03×10^9 kg CO_2 Eq. respectively. The percentage differs by 15%, but the difference in quantity seems more significant as it is estimated at 0.72×10^9 kg CO_2 Eq.

It is worth noting that even with the same LNG propulsion system, the environmental impact may vary depending on the ship power and type. For instance, in the section where the vessel power is within the point A, the difference in environmental impacts between ship types can increase by up to 50%. The rest of sections represents a relatively narrow gap - about 15%.

As one noticeable point to be emphasized is that bulk carriers and container ships have attributed to the largest share (42%) of CO_2 emissions related to maritime activities between 2013 and 2015, which corresponds to nearly 1 billion tonnes of CO_2 (Lowell et al., 2013).

One of the reasons why bulk carriers and container ships have a greater environmental impact than other ship types could be due to the influence of the number and power range of ships in whole fleet. Also, the range of distribution of each ship type in the database of the entire fleet could also have an effect. For example, since an LNG carrier has a higher power range on average than other ship types, it can be estimated that the higher the power, the more environmental impacts it has than other ships. However, since the number of LNG carriers in the entire fleet is smaller than that of bulk and container ships, it does not show a dramatic difference.

Above all, the results of PT-LCA were represented as the association between two variables (ship types and environmental potentials) under various engine power and type scenarios. Those equations were found to be useful in evaluating and comparing emissions in different scenarios. Therefore, it is highly expected that this approach will ultimately confirm whether a certain ship can achieve the IMO’s ambitious goal of 50% GHG reduction by 2050 compared to the 2008 level.

6.4.2. Comparison of engine types (including HFO fueled engine)

Figure 6-6 indicates the results of WTW environmental impacts of LNG engines with maximum value. In particular, Figure 6-6(a) to Figure 6-6(d) show the GWP of each engine under different ship types. Except for GHG emissions, very identical trends are observed in the results. Similar to some recent LNG studies (Pavlenko et al., 2020; Sharafian et al., 2019), those trends suggest that the LS-HPDF series engines can offer benefits for reducing lifecycle GHGs compared to HFO usage. In contrast, all other engine types have been shown more harmful than the conventional diesel product in terms of GWP. The MS-LPDF engines were estimated to produce the highest levels of GWP, while the LS-LPDFs would emit less than MS-LPDF engines, but slightly more than the LSDs.

For example, Figure 6-6(a) shows that, with a vessel power having 10,000kW, LS-HPDF engines were estimated to produce 1.21×10^9 kg CO2 Eq., LSD engines are to release 1.41×10^9 kg CO_2 Eq., whereas MS-LPDF engines are to emit 1.63×10^9 kg CO_2 Eq.. The rest of ship types depicted in Figure 6-6(b), (c) and (d) also are also in a similar trend. As shown in Figure 6-6(c) for LNG carriers with a vessel having an engine power of 10,000kW, LS-HPDF engines are expected to emit 6.32×10^8 kg CO_2 Eq., LS-LPDF engines are predicted to produce 7.55×10^8 kg CO_2 Eq.. The LSD engines are at 7.98×10^8 kg CO_2 Eq. and MS-LPDF engines are to emit 8.83×10^8 kg CO_2 Eq.

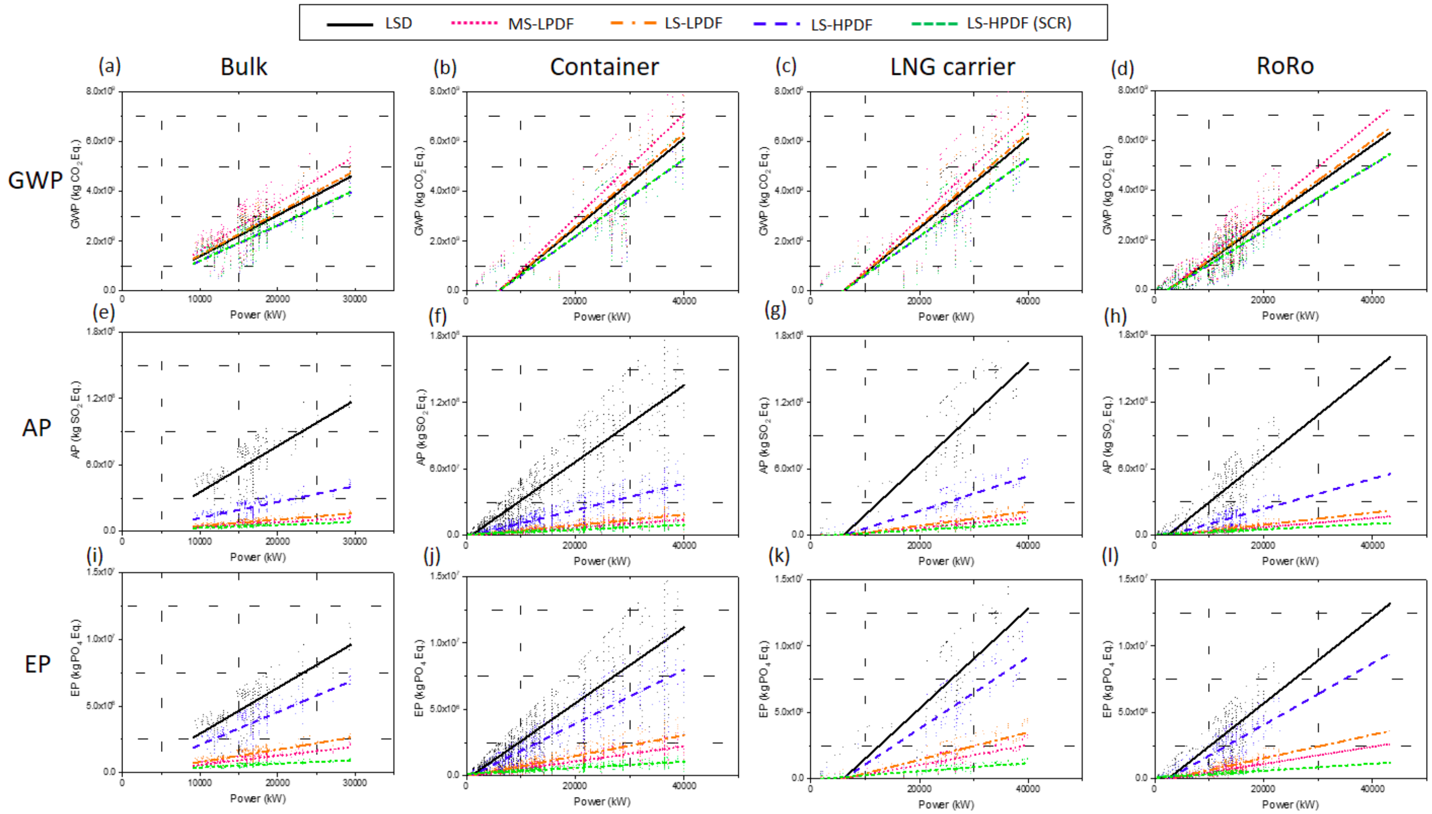

Figure 6-6: Results of comparison of engine type through parametric trend LCA describing environmental impacts according to engine power [kW]: Lifespan of a ship is 30 years, WTW environmental impacts which are GWP, AP and EP trends for the four engine types (LSD – Black solid line, MS-LPDF - Red short dot line, LS-LPDF - Orange dash dot line, LS-HPDF - Blue dash line, LS-HPDF(SCR) - Green short dash dot line), (a) Bulk, GWP according to ship power [kW], (b) Container, GWP according to ship power [kW], (c) LNG carrier, GWP according to ship power [kW], (d) Ro-Ro, GWP according to ship power [kW], (e) Bulk, AP according to ship power [kW], (f) Container, AP according to ship power [kW], (g) LNG carrier, AP according to ship power [kW], (h) Ro-Ro, AP according to ship power [kW], (i) Bulk, EP according to ship power [kW], (j) Container, EP according to ship power [kW], (k) LNG carrier, EP according to ship power [kW], (l) Ro-Ro, EP according to ship power [kW].

Although it is clear that the greater the ship's power, the more it affects the environment, the incremental slopes vary depending on the engine types.

In Figure 6-6(a), when a vessel power is 10,000kW, the difference between LS-HPDF and LSD are marked at 0.20×10^9 kg CO_2 Eq. On the other hand, the gap significantly rises along with the increment in power; at 35,000 kW, the difference in emission level between LS-HPDF and LSD is about 0.76×10^9 kg CO_2 Eq. That means that the relative percentage of CO_2 Eq. emissions difference between LS-HPDF and LSD at 10,000 kW and at 35,000 kW is about 26%.

However, as shown in Figure 6-6(e) - Figure 6-6(l), all other LNG engine systems are much smaller in AP and EP than LSDs. Among them, MS-LPDF engines, that emit the highest GHG emissions, produce less SO_x and NO_x emissions than LS-HPDF and LS-LPDF engines. On the contrary, LS-HPDF engines emit more SO_x and NO_x emissions than the other two LNG engines, but it also reveals that LS-HPDF (SCR) can lower AP and EP to the lowest level.

Figure 6-6 (e) shows, at 10,000kW, MS-LPDF engines are estimated to emit 3.78×10^6 kg SO_2 Eq., LS-LPDF engines are at 4.97×10^6 kg SO_2 Eq., LS-HPDF engines are at 1.24×10^7 kg SO2 Eq., LSD engines are at 3.57×10^7 kg SO_2 Eq. and LS-HPDF (SCR) engines are at 3.21×10^6 kg SO_2 Eq. These results imply that MS-LPDF engines can reduce AP by 90% when compared to LSD engines; LS-HPDF engines are predicted to achieve a 65% AP reduction and LS-HPDF (SCR) engines can further accomplish a 91% reduction.

In Figure 6-6(i), the EP trends are less dramatic than the AP while showing the similar trends. At 10,000kW, MS-LPDF engines are estimated to emit 5.86×10^5 kg PO_4 Eq., LS-LPDF engines would emit 8.08×10^5 kg PO_4 Eq., LS-HPDF engines are for 2.1×10^6 kg PO_4 Eq., LSD engines are for 2.94×10^6 kg PO_4 Eq. and LS-HPDF (SCR) engines are for 3.82×10^5 kg PO_4 Eq. MS-LPDF engines are found to reduce EP by 80% more than LSD engines; LS-HPDF engines and LS-HPDF (SCR) can reduce EP by 30% and by 87% respectively.

Research findings point out that AP and EP have stronger associations with ship power than GWP. It can also be further inferred that LS-HPDF (SCR) engines could be the best option in response to cleaner shipping regardless of the ship type. In fact, LS-HPDF engines without SCR have a strong advantage of reducing GWP, but it is not effective at reducing AP and EP. The LS-LPDF and MS-LPDF engines are not better than HFOs in terms of GWP but have a huge advantage in reducing APs and EPs.

In this section, the most eco-friendly LNG engine type was disclosed as LS-HPDF (SCR) in various scenarios. The engine power has a positive relation with the level of emission reduction compared to HFO. Although LNG is not a zero-emission fuel, research findings provide some implications that it can be better used as a bridge fuel between HFO and low carbon fuels if the engine can be selected appropriately given the ship's power and type.

6.4.3. Comparison of WTT and TTW

Figure 6-7 shows the results of comparative analysis between WTT and TTW environmental impact trends when each engine type is associated with bulk carriers. This clearly shows that TTW produces significantly more emissions than WTT. For example, in terms of GWP, when a vessel with the power of 10,000 kW, a LS-HPDF engine would produce 4.48×10^8 kg CO_2 Eq. in WTT stage, while the same engine would emit 7.72×10^8 kg CO_2 Eq. in TTW. Similarly, LS-LPDF and MS-LPDF engines also reveal to produce twice as many emissions in TTW than in WTT.

Likewise, in the AP and EP, TTW has more impacts than WTT, though the gap is far larger than GWP. In particular, the significant difference is found more noticeable in LS-HPDF than MS-LPDF. For example, at 10,000 kW, MS-LPDF engines emit 1.23×10^6 kg SO_2 Eq. during WTT and emit 2.55×10^6 kg SO_2 Eq. for TTW. In the meantime, LS-HPDF engines emit 1.07×10^6 kg SO_2 Eq. for WTT and emit 1.13×10^7 kg SO_2 Eq. for TTW. If MS-LPDF engines are fitted onboard, WTT would produce two times more emissions than TTW. However, if LS-HPDF engines are considered, the gap increases by ten times. Since LS-HPDF engines emit NOx contributing to AP about 6 times more than MS-LPDF engines, the environmental impacts between WTT and TTW in LS-HPDF engines are remarkable compared to MS-LPDF engines as the engine power increases. Therefore, it can be confirmed that the contribution of TTW to the marine environment, in terms of AP and EP, is much higher with HPDF engines than LS-LPDF or MS-LPDF engines.

Meanwhile, LS-HPDF (SCR) engines tend to be slightly different from other engines. In terms of GWP, it is almost identical to LS-HPDF engines. However, the difference between WTT and TTW in AP and EP is much less than that of the other three engines, as the SCR system significantly reduced NOx emissions in TTW stage. Even in EP, WTT started to have a higher value than TTW at about 2,5000 kW. Eventually, it was confirmed that the SCR system could achieve a substantial reduction in AP and EP from a life cycle perspective.

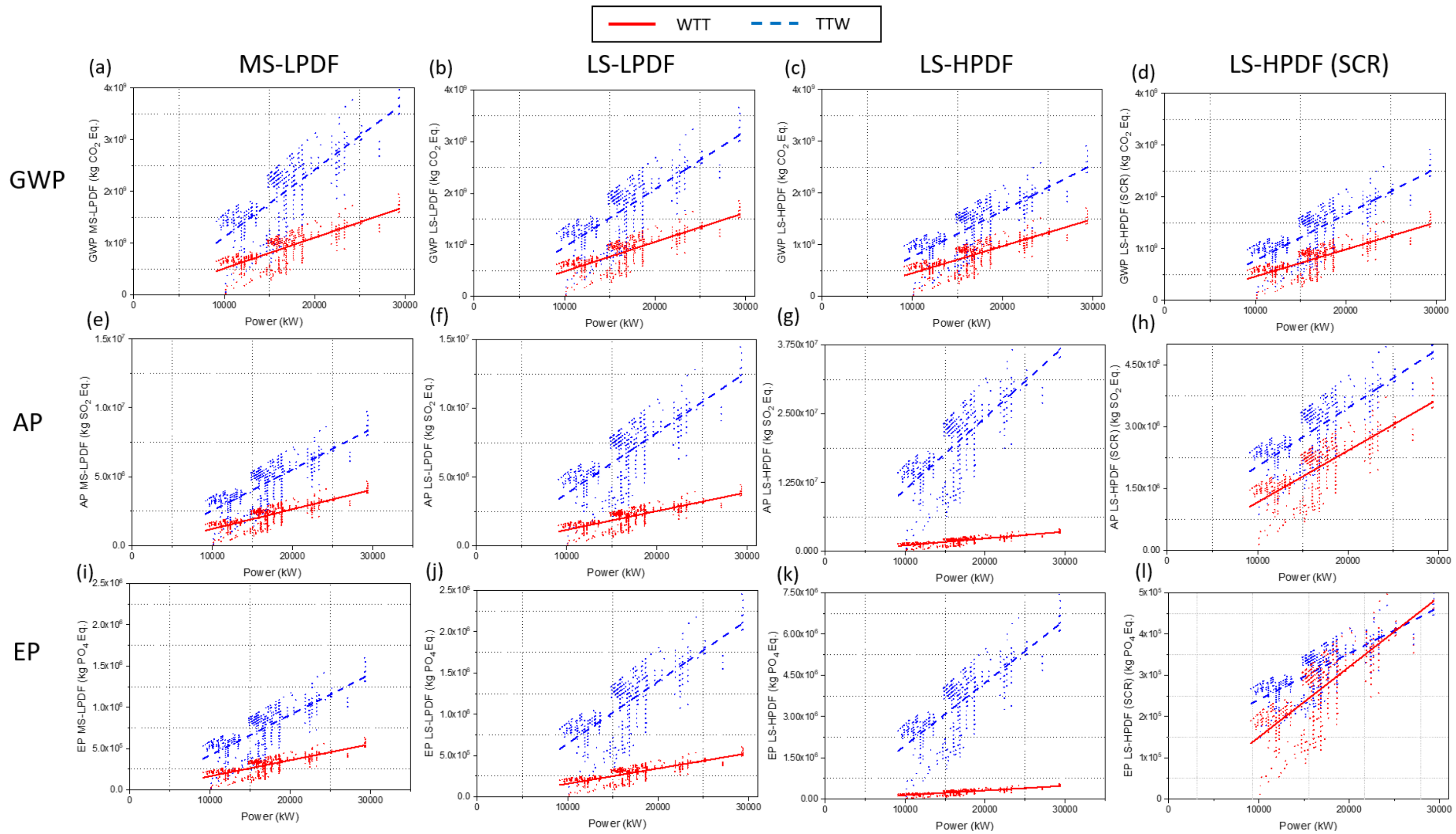

Figure 6-7: Results of comparison of WTT and TTW through parametric trend LCA describing environmental impacts according to power [kW]: Lifespan of a ship is 30 years, WTT and TTW environmental impacts which are GWP, AP and EP trends for the bulk ships (WTT – Red solid line, TTW - Blue dash line). (a) MS-LPDF, GWP according to ship power [kW], (b) LS-LPDF, GWP according to ship power [kW], (c) LS-HPDF, GWP according to ship power [kW], (d) LS-HPDF (SCR), GWP according to ship power [kW], (e) MS-LPDF, AP according to ship power [kW], (f) LS-LPDF, AP according to ship power [kW], (g) LS-HPDF carrier, AP according to ship power [kW], (h) LS-HPDF (SCR), AP according to ship power [kW], (i) MS-LPDF, EP according to ship power [kW], (j) LS-LPDF, EP according to ship power [kW], (k) LS-HPDF, EP according to ship power [kW], (l) LS-HPDF (SCR), EP according to ship power [kW].

6.4.4. Comparison of Maximum and Minimum pathways

Figure 6-8 to Figure 6-11 show environmental impact results depending on maximum and minimum pathways of each LNG engine type with 95% confidence interval. The red line indicates the WTW environmental impacts taking the maximum pathway, whereas the blue line illustrates the same stage taking the minimum pathway, and the black line indicates WTW for LSD engines.

A common observation through those figures is that the difference in GWP between the maximum and minimum pathways for each engine is clearly distinguished. In the case of MS-LPDF and LS-LPDF engines (see Figure 6-8 & Figure 6-9), the AP and EP show a little difference in the maximum and minimum pathways, but the GWP emitted more GHG than the LSD engines. The minimum pathway emits less emission than LSD engines. Research findings have shown that WTT's methane leak will be a key issue to enable MS-LPDF and LS-LPDF engines to contribute to GHG emission reduction.

According to section 6.3.1., such a distinction observed between the maximum and the minimum pathways can be mainly due to the disparate scenarios of logistics; the maximum pathway covers the NG transport between the extraction and liquefaction processes via the pipeline, but the minimum pathway does not consider it. This result suggests that it may be possible to reduce GHG emissions by reducing the logistic activities which are sensitive to distance from extraction to the liquefaction points and transport means.

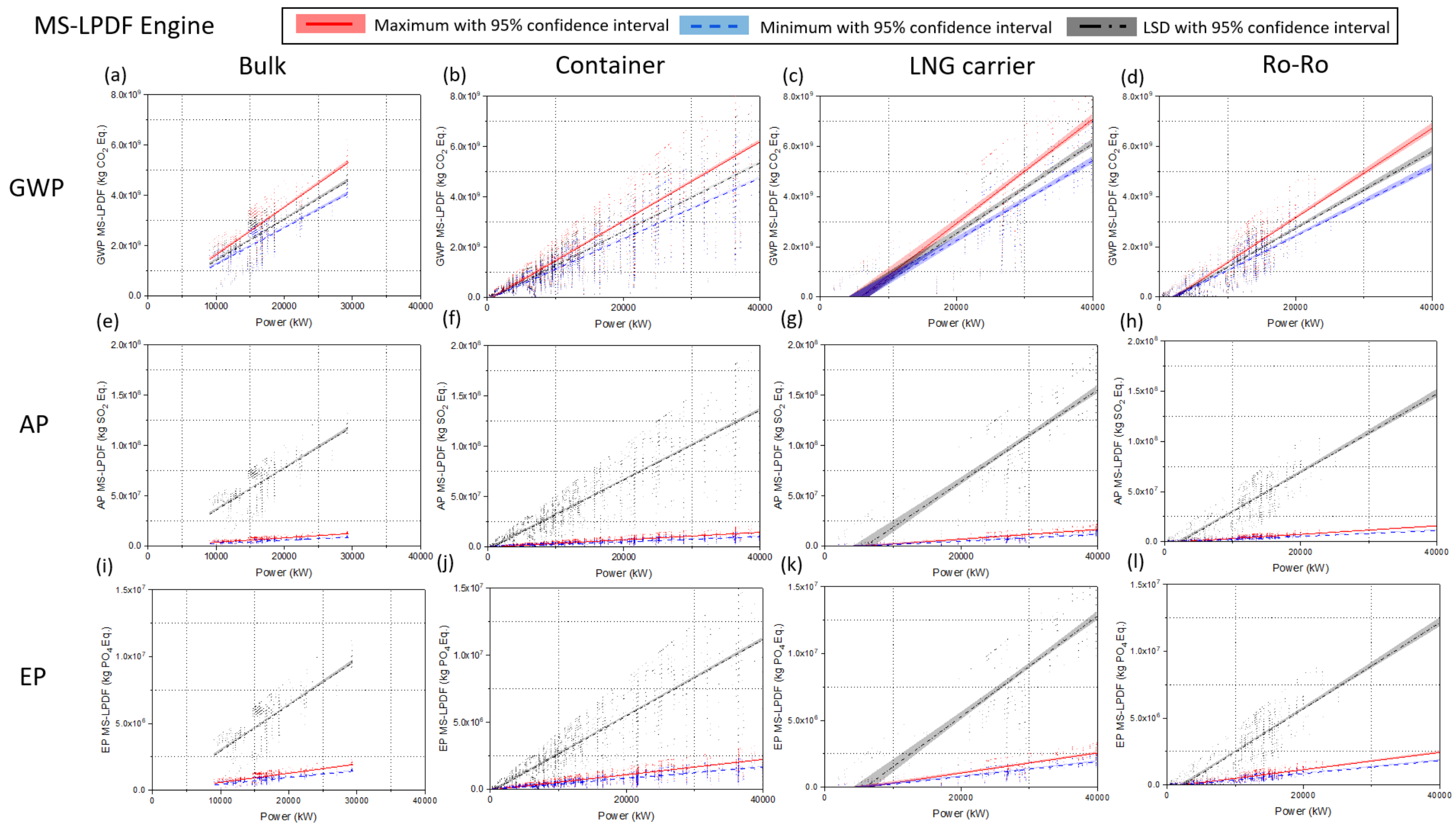

Figure 6-8: Environmental impact results of Maximum & Minimum pathways of the MS-LPDF engine with 95% confidence interval: Lifespan of a ship is 30 years, WTW Maximum pathways – Red solid line, WTW Minimum pathways - Blue dash line, WTW LSD – Black short dash dot line. (a) Bulk, GWP according to ship power [kW], (b) Container, GWP according to ship power [kW], (c) LNG carrier, GWP according to ship power [kW], (d) Ro-Ro, GWP according to ship power [kW], (e) Bulk, AP according to ship power [kW], (f) Container, AP according to ship power [kW], (g) LNG carrier, AP according to ship power [kW], (h) Ro-Ro, AP according to ship power [kW], (i) Bulk, EP according to ship power [kW], (j) Container, EP according to ship power [kW], (k) LNG carrier, EP according to ship power [kW], (l) Ro-Ro, EP according to ship power [kW].

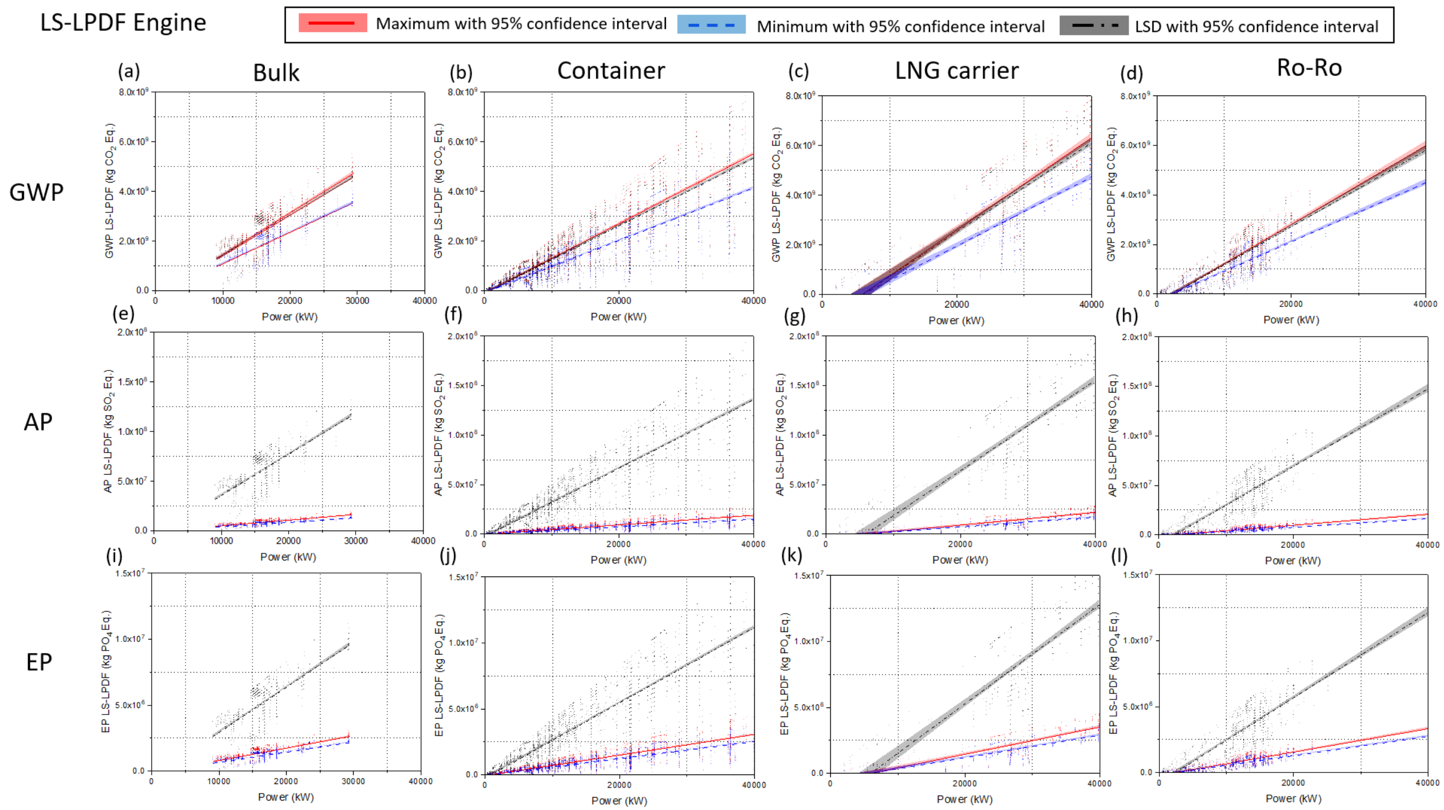

Figure 6-9: Environmental impact results of Maximum & Minimum pathways of the LS-LPDF engine with 95% confidence interval: Lifespan of a ship is 30 years, WTW Maximum pathways – Red solid line, WTW Minimum pathways - Blue dash line, WTW LSD – Black short dash dot line. (a) Bulk, GWP according to ship power [kW], (b) Container, GWP according to ship power [kW], (c) LNG carrier, GWP according to ship power [kW], (d) Ro-Ro, GWP according to ship power [kW], (e) Bulk, AP according to ship power [kW], (f) Container, AP according to ship power [kW], (g) LNG carrier, AP according to ship power [kW], (h) Ro-Ro, AP according to ship power [kW], (i) Bulk, EP according to ship power [kW], (j) Container, EP according to ship power [kW], (k) LNG carrier, EP according to ship power [kW], (l) Ro-Ro, EP according to ship power [kW].

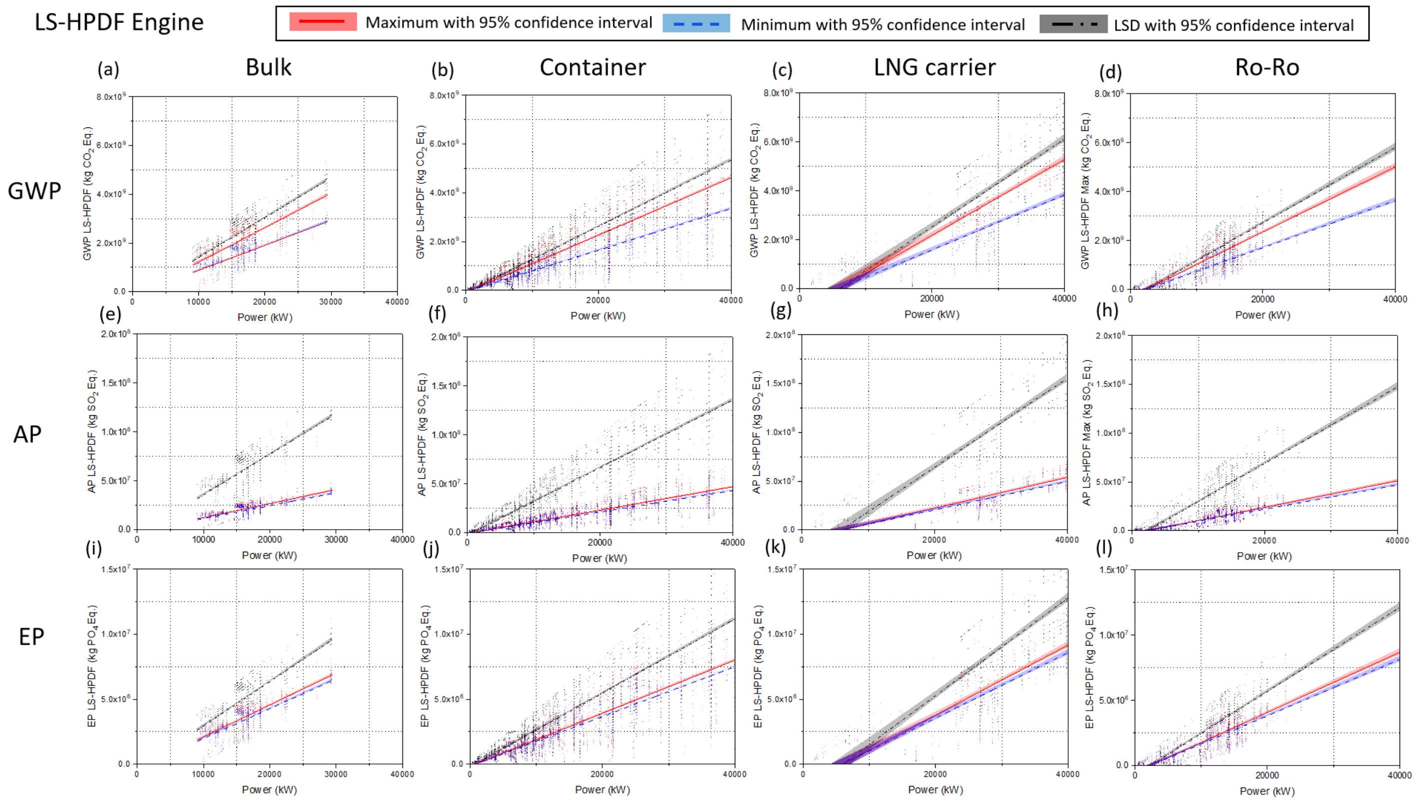

Figure 6-10: Environmental impact results of Maximum & Minimum pathways of the LS-HPDF engine with 95% confidence interval: Lifespan of a ship is 30 years, WTW Maximum pathways – Red solid line, WTW Minimum pathways - Blue dash line, WTW LSD – Black short dash dot line. (a) Bulk, GWP according to ship power [kW], (b) Container, GWP according to ship power [kW], (c) LNG carrier, GWP according to ship power [kW], (d) Ro-Ro, GWP according to ship power [kW], (e) Bulk, AP according to ship power [kW], (f) Container, AP according to ship power [kW], (g) LNG carrier, AP according to ship power [kW], (h) Ro-Ro, AP according to ship power [kW], (i) Bulk, EP according to ship power [kW], (j) Container, EP according to ship power [kW], (k) LNG carrier, EP according to ship power [kW], (l) Ro-Ro, EP according to ship power [kW].

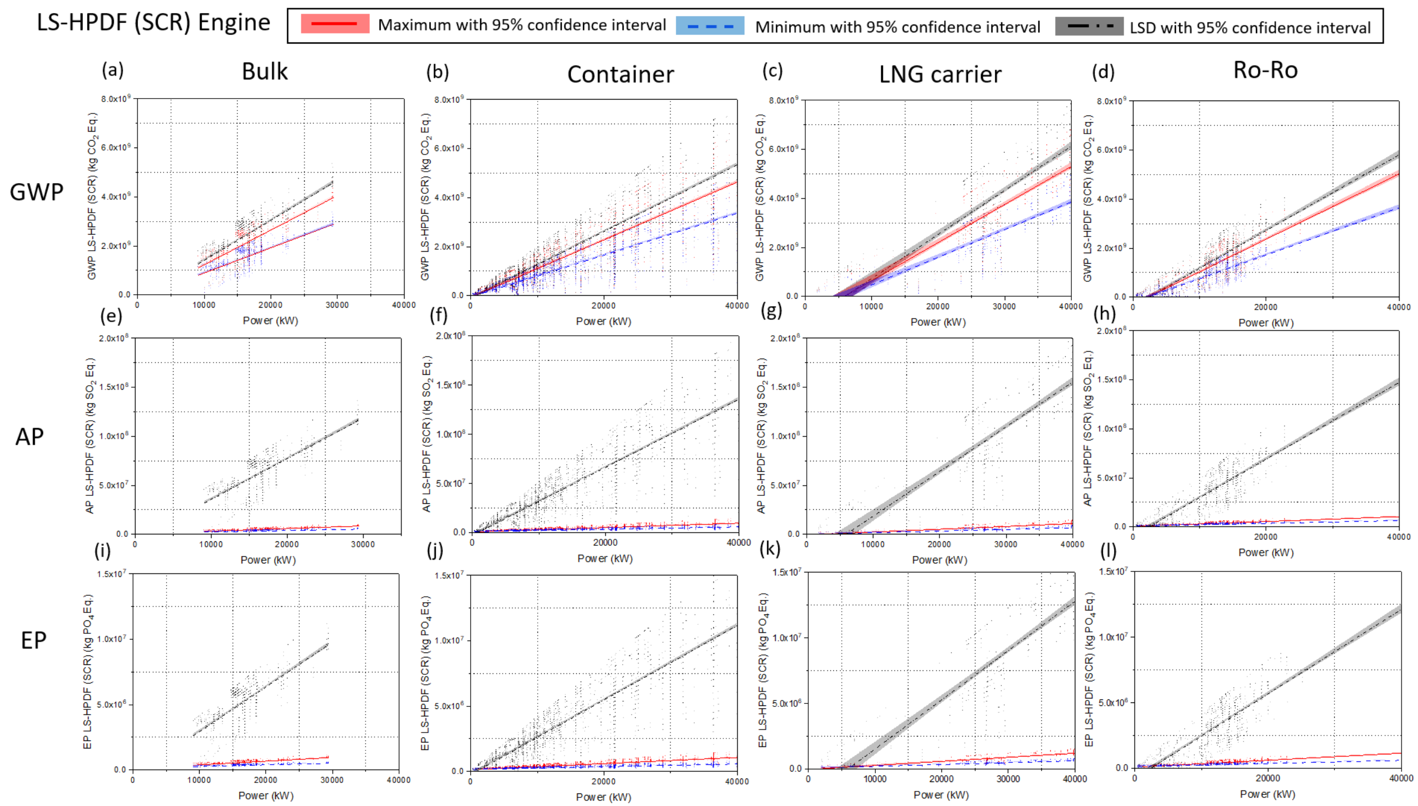

Figure 6-11: Environmental impact results of Maximum & Minimum pathways of the LS-HPDF (SCR) engine with 95% confidence interval: Lifespan of a ship is 30 years, WTW Maximum pathways – Red solid line, WTW Minimum pathways - Blue dash line, WTW LSD – Black short dash dot line. (a) Bulk, GWP according to ship power [kW], (b) Container, GWP according to ship power [kW], (c) LNG carrier, GWP according to ship power [kW], (d) Ro-Ro, GWP according to ship power [kW], (e) Bulk, AP according to ship power [kW], (f) Container, AP according to ship power [kW], (g) LNG carrier, AP according to ship power [kW], (h) Ro-Ro, AP according to ship power [kW], (i) Bulk, EP according to ship power [kW], (j) Container, EP according to ship power [kW], (k) LNG carrier, EP according to ship power [kW], (l) Ro-Ro, EP according to ship power [kW].

In the meantime, comparing Figure 6-8 with Figure 6-9 and Figure 6-10, unlike engines, the LS-HPDF engine is superior to the MS-LPDF and LS-LPDF in reducing GHG, but has some limitations for diminishing AP and EP.

No significant differences are found in the maximum and minimum paths in terms of AP and EP, but the differences for each engine type were noticeable in the GWP. Specifically, for WTT's maximum path, the MS-LPDF and LS-LPDF engines are less green than HFOs in terms of GWP, but it could be greener if the shortest transport routes and minimum transport means were secured.

Thus, although section 6.4.2. concluded LS-HPDF (SCR) engines would be the only option to guarantee the excellence of GWP reduction when compared to HFO engines, the research finding stated in this section provided an insight MS-LPDF and LS-LPDF could also be an option to reduce GWP on the condition of optimized WTT pathway.

Regarding the WTT and TTW of LNG, the results discussed in Section 6.4.3 offered an insight that the aspect of the use of LNG is much more important to the environment than the production phase of LNG. However, as discussed in this Section 6.4.4, even though LNG engines such as LS-LPDF and MS-LPDF have shown higher GWP compared to LSDs, if WTT produces LNG through minimum pathway, it can be more environmentally friendly than conventional diesel engines regardless of LNG engine types. By expanding this result, it may also be possible to study whether the green shipping goal can be ultimately achieved when the entire fleet use LNG produced by the minimum pathway with the LS-LPDF or MS-LPDF engine. In other words, using PT-LCA, it is achievable to access wide range studies where existing LCA studies are difficult to approach with only a few case ships.

6.4.5. Comparison of engine types

Figure 6-12 compares the environmental impacts of engine types in order to confirm the adequacy of statistical analysis in the previous findings. In comparison, it was to determine whether the difference in engine types should result in differences in environmental impacts substantially.

The findings are highly consistent with what were presented in the previous sections. Regardless of ship types, for the GWP, the order from the greatest to the least is MS-LPDF, LSD, LS-LPDF, LS-HPDF and LS-HPDF (SCR). In AP, LSD shows the highest, followed by the MS-LPDF, LS-LPDF and LS-HPDF (SCR). Although EP shows a wider distribution than AP, the order of environmental impact is displayed the same as AP.

For example, Figure 6-12(a) indicates MS-LPDFs emits 3.0×10^9 kg CO_2 Eq., LS-LPDFs emits 2.8×10^9 kg CO_2 Eq., LS-HPDFs emits 2.4×10^9 kg CO_2 Eq., LSDs emits 2.8×10^9 kg CO_2 Eq., and LS-HPDF(SCR)s emits 2.4×10^9 kg CO_2 Eq on average. In a similar pattern, Figure 6-12(b) indicates MS-LPDF emits 1.9×10^9 kg CO_2 Eq., LS-LPDF emits 1.8×10^9 kg CO_2 Eq., LS-HPDF emits 1.5×10^9 kg CO_2 Eq., LSD emits 1.8×10^9 kg CO_2 Eq., and LS-HPDF(SCR) emits 1.5×10^9 kg CO_2 Eq on average.

On the other hand, it should be mentioned that Figure 6-12 cannot be used as indicators to compare environmental impacts of different ship types. To be specific, LNG carriers in Figure (c) appear higher environmental impacts than bulk carriers in Figure 6-12 (a). It is not because the ship type of LNG carrier produces more emissions than the type of bulk carrier but because the LNG carriers are generally larger in size than bulk carriers in the world fleet database.

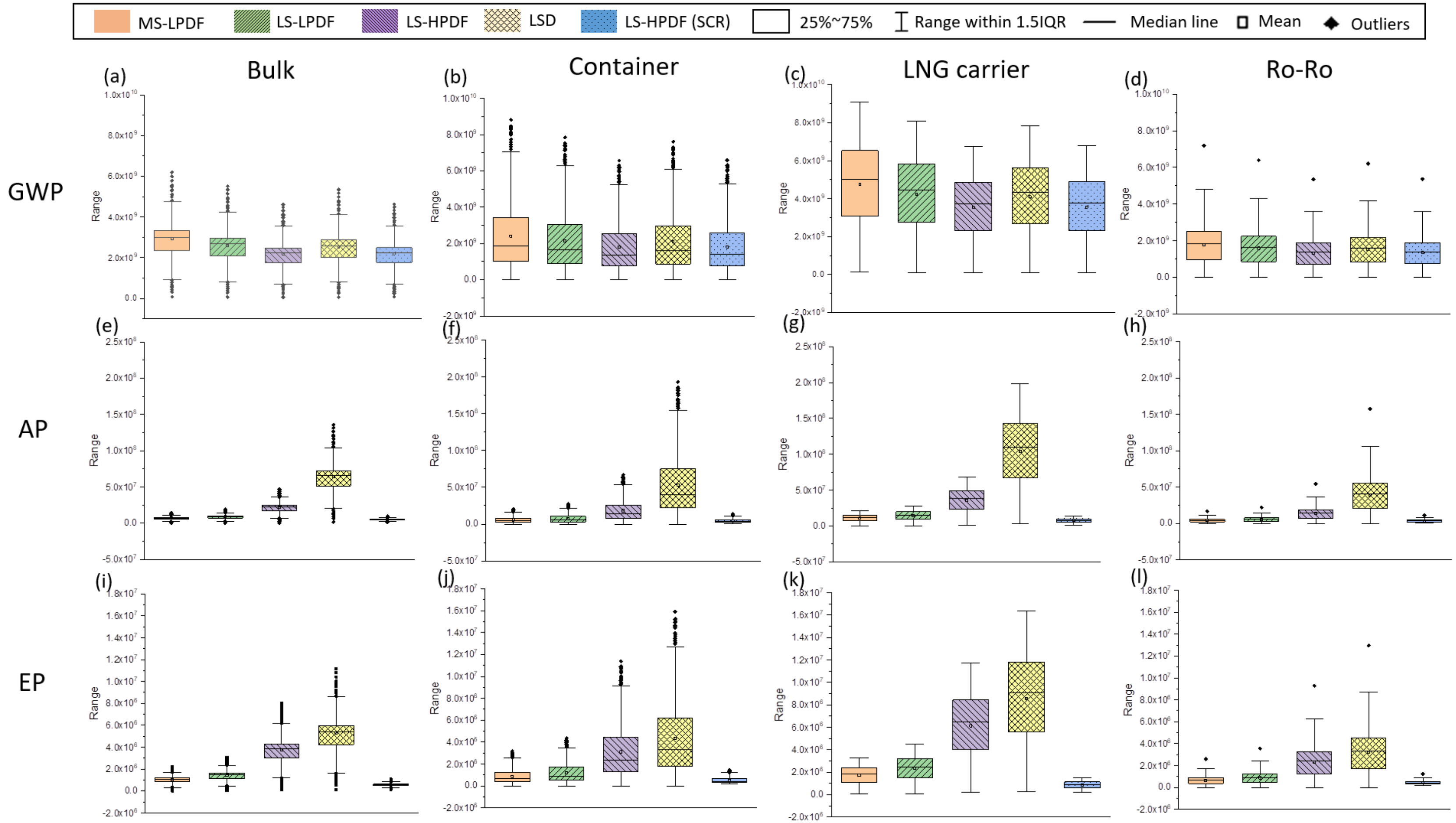

Figure 6-12: Box plot chart results of engine types according to ship types: Lifespan of a ship is 30 years, MS-LPDF engine – Orange box, LS-LPDF engine – Green box, LS-HPDF engine – Purple box, LSD engine – Yellow box, LS-HPDF (SCR) engine – Blue box. (a) GWP of Bulk, (b) GWP of Container, (c) GWP of LNG carrier, (d) GWP of Ro-Ro, (e) AP of Bulk, (f) AP of Container, (g) AP of LNG carrier, (h) AP of Ro-Ro, (i) EP of Bulk, (j) EP of Container, (k) EP of LNG carrier, (l) EP of Ro-Ro.

6.5. Concluding remarks

This chapter was to answer a fundamental question on whether LNG truly contribute to reducing environmental impacts from shipping activities. Given this, it was intent to determine the holistic association between LNG and environmental impacts. To obtain a general observation, the analysis was coupled with the extensive dataset of over 7,000 ships consisting of bulk carriers, container ships, LNG carriers and Ro-Ro ships under various scenarios. Results demystified the environmental strengths and limitations of LNG engines that fell into three representative types: low-speed high-pressure dual-fuel engines, low-speed low-pressure dual-fuel engines, and medium-speed low-pressure dual-fuel engines. The first engine type was confirmed effective compared to diesel fuel, whereas the other two types required further optimization. Research findings also revealed that the operational phase generally contributed twice the global warming effect and about ten times more local pollutants than the production phase. A substantial contribution to the industry could be made by the environmental equations developed in this chapter. They are highly expected to help stakeholders to break through the discrepancy problem raised in previous studies that were so different from case to case that the scope, boundary of analysis, data, and assumptions they used were far away from contributing to standardization. In addition, the proposed approaches taken to develop those equations are also strongly believed to offer a meaningful insight into future regulatory and decision-making frameworks.

7. PARAMETRIC TREND LIFE CYCLE ASSESSMENT FOR HYDROGEN FUEL CELLS

7.1. Introduction

Based on the previous chapter, it was revealed that PT-LCA can be applied to alternative fuels and systems for ships, and meaningful results were obtained. In this chapter, the scope of application of PT-LCA has been expanded by applying to hydrogen fuel cells that are still under development but are expected to be a more advanced and innovative fuel in the future.

7.2. Goal and scope

7.2.1. General scope

As shown in Figure 7-1(a), this chapter evaluates the overall environmental impacts of hydrogen produced in various ways over the entire life cycle from WTW (well-to-wake). It was divided into two sections: WTT (well-to-tank) which is from extraction of fuel to distribution and TTW (tank-to-wake) which is from a fuel tank of ship to fuel consumption to operate ship.

In the WTT analysis, four representative methods for hydrogen production (steam methane reforming (SMR), cracking, electrolysis, and coal gasification) including the energy conversion, supply, and transportation stages were taken into account. The same scope of works was applied to LNG and diesel fuels. TTW analysis deals with the environmental impacts of those fuels consumed by onboard fuel cells; such as, proton exchange membrane fuel cell (PEMFC), molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC) were considered as the representative types for the marine application (Sharaf & Orhan, 2014).

The assumed LCA system can be summarized as follows.

- Given the stringent regulations that primarily deal with GHG, SOx and NOx emissions from shipping industry, which are ultimately linked to GWP, AP and EP respectively, those key environmental impacts were selected as the most prominent indicators.
  - Global Warming Potential (GWP): The IMO aims to halve the 2008 level of carbon dioxide emissions by 2050. Currently, CO_2 (a major contributor to GWP) emissions are controlled by enabling efficient use of ship energy through energy efficiency design index (EEDI), energy efficiency operational indicator (EEOI), and ship energy efficiency management plan (SEEMP).
  - Acidification Potential (AP): Sulphur content (AP Contributors) regulated by IMO MARPOL Annex VI Rule 14 can acidify soils and sea due to the acidity of air pollutants.
  - Eutrophication Potential (EP): Regulated by IMO MARPOL Annex VI Rule 13, nitrogen oxides (EP contributors) are emitted during the combustion of marine engines and add excess nutrients to soils and sea.
- Hydrogen subject to the analysis is assumed to be 100% pure hydrogen.
- The life cycle impacts of marine fuels is much greater than these of marine propulsion systems such as fuel cells; the environmental impact of systems has been seen negligible compared to the life cycle of fuels (Jeong et al., 2019). Therefore, this study does not consider the WTW impacts of fuel cell systems.
- Lifespan of vessel is assumed to be 20 years without berthing or anchoring.
- The functional unit for PT-LCA are represented as functional equations which are mathematic equations expressing correlations between ship basic information and environmental impacts.
- In the functional equation, x value is ship power, and x value must be within the used ship data power value. It should also be reliable as an R-squared with a consistency range of 60%-80% in linear regression.

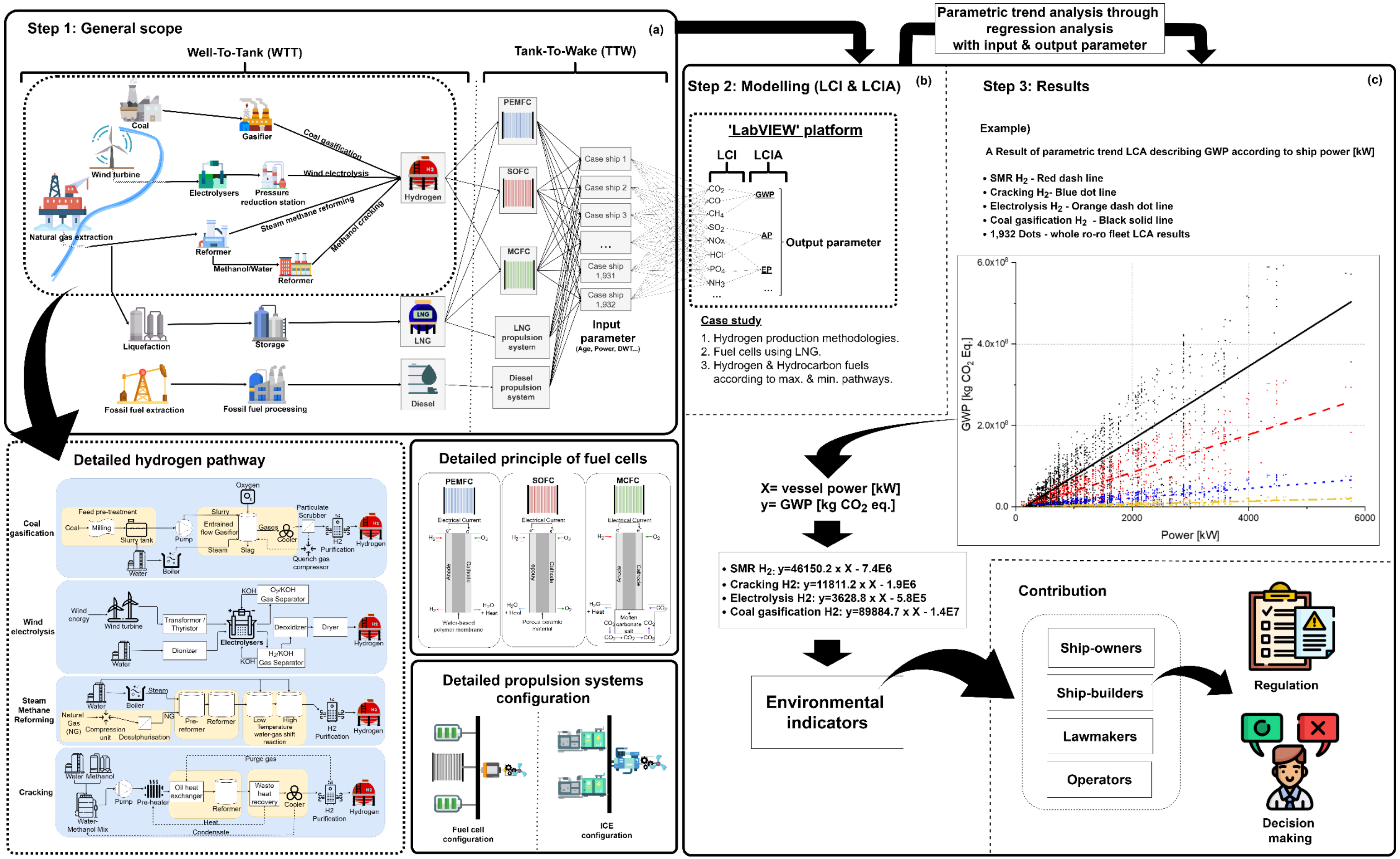

Figure 7-1. Overview of hydrogen fuel cell PT-LCA with detailed hydrogen pathway, configurations of related systems.

Hydrogen is one of the most abundant elements in the universe, but because of its high reactivity, it primarily exists on Earth as compounds such as water, oil, natural gas, and methanol. For this reason, hydrogen production is based on the principle of removing other molecules from those compounds (Steinberger-Wilckens et al., 2017).

Hydrogen production methods have been developed in various ways. While vigorous efforts have been made to find the optimal production method in terms of environmental and economic aspects, the four representative technologies are widely acknowledged at present: 1) using steam reforming; 2) using cracking technology, 3) the electrolysis method 4) coal gasification.

The first and second methods are known as the most economical, occupying a large portion of the current hydrogen production market. The third one is the most environmentally friendly method to produce green hydrogen using wind energy. Finally, the fourth one is another possible method of producing hydrogen via coal gasification in a high-temperature and high-pressure reactor.

7.2.2. Data collection

The data on total 1,932 ships of small vessels under 500 GT (Gross tonnage) based on hydrogen fuel cells were collected from the Lloyd's Register marine database. To be specific, Figure 7-2 shows the number of ships according to the age, power, and dead weight tonnage (DWT) of the ship used in this research.

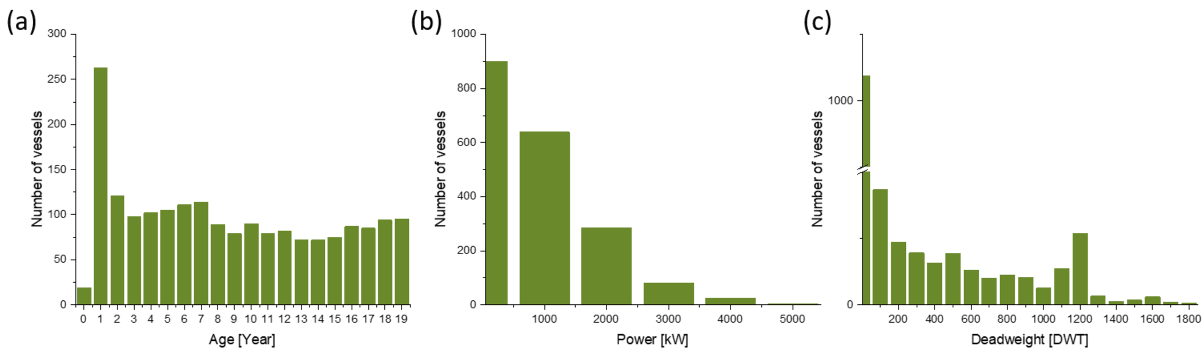

Figure 7-2. Distribution chart of vessels database according to major input parameters: (a) vessel numbers according to age (Year), (b) vessel numbers according to power (kW) and (c) vessel numbers according to deadweight (DWT).

Given that the lifespan of the ship was assumed to be up to 20 years, ships with a lifespan of one year were the most common with more than 250 ships, and ships with a lifespan of 2 to 20 years had a general distribution of about 100 on average. In terms of power, ships under 1,000 kW account for about half of the total, and ships with less than 100 DWT had the widest distribution.

7.3. Modelling

As shown in Figure 7-1(b), the modelling phase of the PT-LCA incorporates the life cycle inventory (LCI) and life cycle impact assessment (LCIA) steps to design an established platform that can connect with thousands of sample databases simultaneously.

7.3.1. Well-to-tank (WTT) environmental impacts

Figure 7-1(a) illustrates the WTT pathways of existing LCA studies for the four hydrogen production methods: SMR, cracking, electrolysis, coal gasification. Table 7-1 indicates the characterization factors for GWP, AP and EP obtained from several LCA results and Table 7-2 presents the results of the estimating the environmental impacts based on Table 7-1. It can be clearly observed that the results are inconsistent due to limitations inherent in conventional LCA and vary depending on the studies and data used.

In response, the PT-LCA was designed to reveal the full range of environmental impacts in consideration of the gaps between the maximum and minimum values. These figures are calculated on the PT-LCA platform and reproduced as thousands of results when applied to the entire fleet.

Table 7-1. LCIA information including characterization factor for selected environmental impact categories.

Impact categories [Unit]	Characterization factors	Original reference
GWP [kg CO_2 eq.]	1 CO_2, 28 CH_4, 265 N_2O	(Stocker et al., 2013)
AP [kg SO_2 eq.]	1.88 NH_3, 0.7 NO_2, 1 SO_x	(van Oers, 2016)
EP [kg PO_4 eq.]	1 PO_4, 0.35 NH_3, 0.022 COD, 013 NO_x	(van Oers, 2016)

Table 7-2. Existing environmental impacts results of WTT hydrogen including GaBi database.

		GaBi database					
		Europe	Netherlands	Germany	(Cetinkaya et al., 2012)	(Spath & Mann, 2000), (Spath & Mann, 2004)	(Siddiqui & Dincer, 2019), (Mehmeti, Angelis-Dimakis, Arampatzis, McPhail, & Ulgiati, 2018)
GWP ($kg\ CO_2$ eq./H_2 kg)	SMR	8.20×10^{0}	1.03×10^{1}	1.06×10^{1}	1.12×10^{1}	1.24×10^{1}	-
	Cracking	1.75×10^{0}	-	3.18×10^{0}	-	-	-
	Coal gasification	-	-	-	-	-	2.37×10^{1}, 2.42×10^{1}
	Electrolysis	9.77×10^{-1}	-	-	9.61×10^{-1}	9.72×10^{-1}	-
AP ($kg\ SO_2$ eq./H_2 kg)	SMR	2.17×10^{-2}	3.02×10^{-3}	4.31×10^{-3}	7.41×10^{-3}	1.81×10^{-2}	-
	Cracking	3.51×10^{-3}	-	4.43×10^{-3}	-	-	-
	Coal gasification	-	-	-	-	-	1.10×10^{-2}, 1.39×10^{-1}
	Electrolysis	4.95×10^{-3}	-	-	6.13×10^{-3}	9.39×10^{-3}	-
EP (kg Phosphate eq./H_2 kg)	SMR	3.48×10^{-3}	5.38×10^{-4}	5.91×10^{-4}	5.25×10^{-4}	1.60×10^{-3}	-
	Cracking	2.88×10^{-4}	-	5.19×10^{-4}	-	-	-
	Coal gasification	-	-	-	-	-	5.80×10^{-4}, 8.00×10^{-3}
	Electrolysis	2.87×10^{-4}	-	-	6.11×10^{-4}	6.11×10^{-4}	-

In addition, considering LNG for fuel cell systems as well as LNG and diesel propulsion systems were adopted to be fuel, those pathways were assumed showing LNG and diesel emission inventory data in Table 7-3. LNG, after being extracted, is transported liquefied at -162°C through a 1,500 km pipeline, stored and then supplied. Diesel which is heavy fuel oil (HFO), goes through the processes of extraction, refining, transportation, and finally supply.

Table 7-3. LNG & Diesel WTT inventory results (Sharafian et al., 2019).

Characteristic units [g/MJ]	LNG	Diesel
CO_2	2.67×10^{1}	1.86×10^{1}
SOx	2.33×10^{-2}	3.40×10^{-2}
NOx	9.10×10^{-2}	5.50×10^{-2}
CH_4	3.20×10^{-1}	1.60×10^{-1}
PM	4.70×10^{-3}	7.90×10^{-3}

7.3.2. Tank-to-wake (TTW) environmental impacts

The TTW phase is to estimate the environmental impacts associated with shipping activities. In order to calculate hydrogen consumption in fuel cells, the concept of maximum available voltage in the process of fuel cell chemistry is applied. This is to estimate the amount of energy consumed by calculating the difference in energy between the initial and final states of a chemical reaction. This evaluation uses the thermodynamic state function which is Gibbs free energy equation to induce the amount of hydrogen consumption by the fuel cell as follows:

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

Where,

P_e = Electrical power of the fuel cell stack

V_c = Average voltage of one cell in the stack (approximate 0.72 V)

F = Faraday constant (the charge on one mole of electrons, 96485 Coulombs)

The daily operating time and the total lifespan of a vessel was assumed to be 15 hours per day and 20 years respectively, while the electric loads for propulsion and auxiliary systems would keep constant during the operation. Based on the derived equations and these assumptions, total hydrogen consumption over the entire operating time was estimated and applied to the entire vessel fleet to obtain environmental impacts relative to their shipping activities.

In addition, emission characterization factors given in Table 7-4 were applied to estimate the environmental impacts when hydrocarbons such as LNGs are used as fuel in fuel cells.

Table 7-4. Estimated fuel cell emission life cycle inventory results (Darrow, Tidball, Wang, & Hampson, 2015).

Emissions Characteristics	Fuel cell type		
	PEMFC	SOFC	MCFC
NO_x (kg/kWh)	-	-	4.53×10^{-6}
SO_x (kg/kWh)	-	-	4.53×10^{-8}
CO (kg/kWh)	-	-	-
VOC (kg/kWh)	-	-	-
CO_2 (kg/kWh)	5.13×10^{-1}	3.32×10^{-1}	4.44×10^{-1}

For LNG and diesel propulsion systems, it was assumed that a low-speed high-pressure dual-fuel engine (LS-HPDF) and a low-speed diesel cycle engine (LSD) were selected, respectively. Table 7-5 shows the TTW inventory dataset for LS-HPDF and LSD engine.

Table 7-5. LS-HPDF & LSD TTW inventory results (Sharafian et al., 2019).

	LS-HPDF	LSD
Engine efficiency (J/J)	5.00×10^{-1}	5.00×10^{-1}
SFC (MJ/kWh)	6.54×10^{0}	7.19×10^{0}
CO_2 (g/MJ fuel)	6.20×10^{1}	8.01×10^{1}
SOx (g/MJ fuel)	5.70×10^{-2}	1.43×10^{0}
NOx (g/MJ fuel)	1.22×10^{0}	1.61×10^{0}
CH_4 (g/MJ fuel)	1.39×10^{-3} (BRYAN Comer, Olmer, Mao, Roy, & Rutherford, 2017)	1.40×10^{-3} (BRYAN Comer et al., 2017)
CO (g/MJ fuel)	1.10×10^{-1}	9.00×10^{-2}
PM (g/MJ fuel)	1.28×10^{-1} (Stenersen & Thonstad, 2017)	1.97×10^{-1} (BRYAN Comer et al., 2017)

7.4. Results of analysis

7.4.1. Comparison of hydrogen production methods

Figure 7-3(a) - (c) shows the trends of the environmental impacts of WTW on SMR hydrogen, cracking hydrogen, electrolysis hydrogen and coal gasification hydrogen according to the ship power. Each dot shown in the graph represents an individual case ship. Since pure hydrogen is utilized as a fuel, the amount of emission generated by each fuel cell is assumed to be zero.

Table 7-6. Total environmental impacts of WTW hydrogen fuel cell.

	SMR	Cracking	Electrolysis	Coal gasification
GWP [kg CO_2 eq.]	1.01E+11	2.59E+10	7.97E+09	1.97E+11
AP [kg SO_2 eq.]	1.77E+08	3.61E+07	7.66E+07	1.13E+09
EP [kg PO_4 eq.]	2.84E+07	4.23E+06	4.99E+06	6.53E+07

The results in Figure 7-3(a) indicate that coal gasification hydrogen produces the highest value in terms of GWP than the other three options. This trend can be observed more clearly in Table 7-6, that aggregates all the environmental impacts of each vessel. The results of these analysis reveal that hydrogen based on fossil fuel contributes to aggravating the climate change ten times greater than hydrogen based on renewable energy. For example, when a vessel power is 5,000 kW, coal gasification hydrogen and SMR hydrogen emit about 4.5×10^8 kg CO_2 eq. and 2.5×10^8 kg CO_2 eq. respectively over the 20-year lifetime. On the other hand, the use of hydrogen produced by electrolysis is expected to produce about 0.2×10^8 kg CO_2 eq. which is significantly less than the use of hydrogen produced from coal gasification.

Similar trends are observed in AP and EP except for the eco-friendliness of cracking hydrogen and electrolysis hydrogen. In terms of GWP, although cracked hydrogen is less environmentally friendly than electrolysis hydrogen, but it can be a much greener hydrogen production method than coal gasification and SMR-induced hydrogen. Considering AP results, as shown in Figure 7-3(b), hydrogen from cracking emits less emission than even electrolytic hydrogen. For example, at 5,000 kW, the cracked hydrogen is predicted to produce about 0.8×10^5 kg SO_2 eq., whereas electrolytic hydrogen would release double: about 1.8×10^5 kg SO_2 eq. A similar observation is made with EP in Figure 7-3(c).

In addition, the environmental impact of the hydrogen life cycle and ship power shows a strong correlation as the environmental impact increases proportionally as the ship power increases. For example, as shown in Figure 7-3(a), with a vessel with 2,000 kW power, the SMR hydrogen production method is estimated to produce about 1.0×10^8 kg CO_2 eq., while the electrolytic hydrogen would attribute to about 0.1×10^8 kg CO_2 eq., resulting in a 10 time higher impact. However, at 5,000 kW, the SMR hydrogen is to emit about 2.5×10^8 kg CO_2 eq., and the electrolytic hydrogen is expected to release about 0.2×10^8 kg CO_2 eq.: about 20 times gap or even more.

In the meantime, Figure 7-3(d) – Figure 7-3(f) show the trends of the WTW environmental impacts of all types of hydrogen with the case ships. Similar to Figure 7-3(a) to Figure 7-3(c), Figure 7-3(d) to Figure 7-3(f) also show the same results that coal gasification yields the greatest level of emissions, whereas electrolytic and cracked hydrogen could generate the least levels across all environmental potentials. As shown in Figure 7-3(d), a vessel operating over 20 years purely with hydrogen from coal gasification would emit approximately 2.1×10^8 kg CO_2 eq. but with electrolytic hydrogen would emit 0.1×10^8 kg CO_2 eq.

As a result of the research, it was revealed that hydrogen fuel can contribute to reducing lifecycle emissions from shipping activities. However, it was also pointed out the holistic environmental impacts differ significantly from the methods of hydrogen production: cracking, electrolysis, SMR, and coal gasification in order from the best to the worst. As a result of the research, it was revealed that hydrogen fuel can contribute to reducing lifecycle emissions from shipping activities. However, it was also pointed out the holistic environmental impacts differ significantly from the methods of hydrogen production: cracking, electrolysis, SMR, and coal gasification in order from the best to the worst.

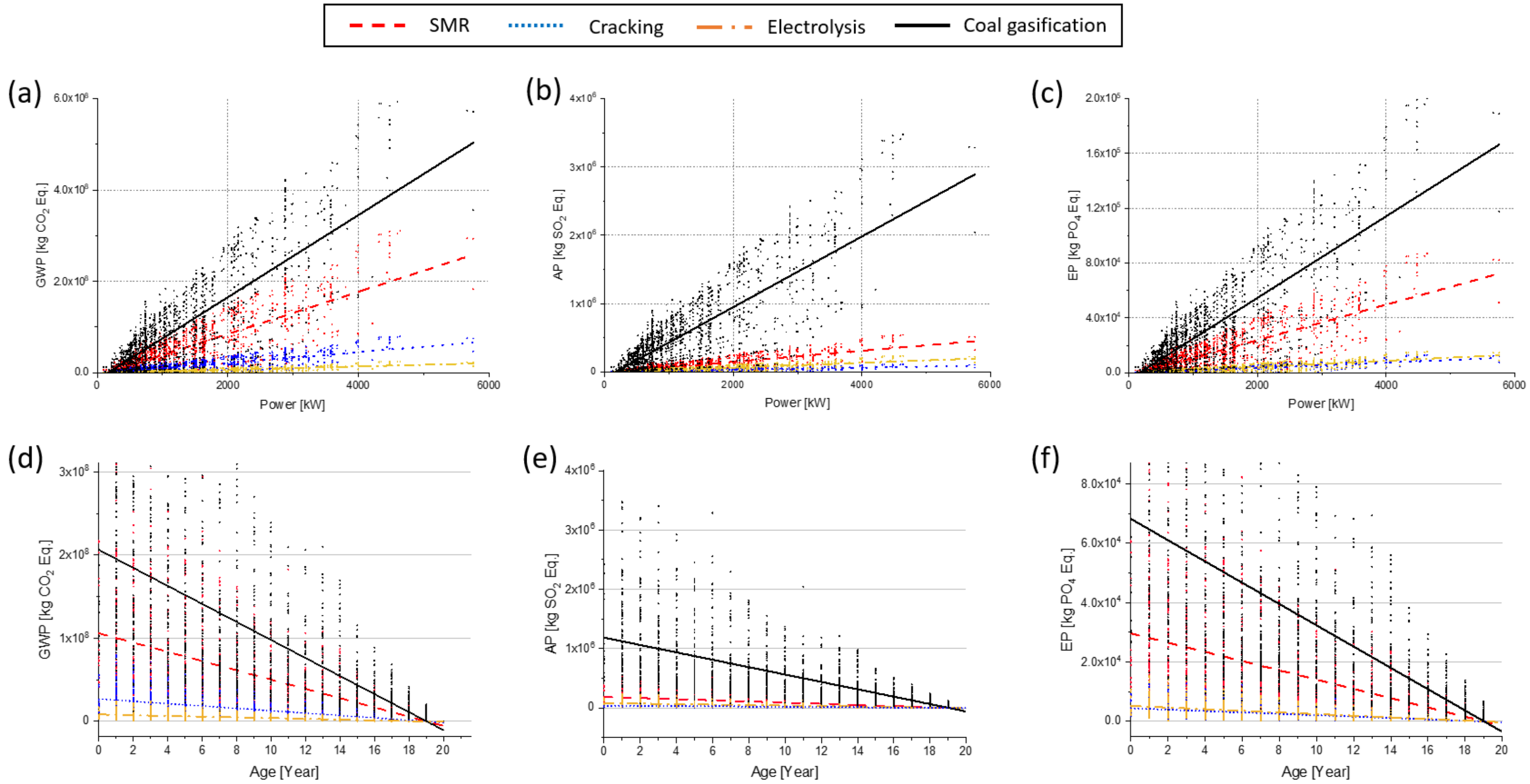

Figure 7-3. Results of comparison of hydrogen production methods through parametric trend LCA describing environmental impacts according to power [kW] & age [Year]: Lifespan of a ship is 20 years, WTW environmental impacts which are GWP, AP and EP trends (SMR H_2 – Red dash line, Cracking H_2 - Blue dot line, Electrolysis H_2 - Orange dash dot line, Coal gasification H_2 - Black solid line), (a) GWP according to ship power [kW], (b) AP according to ship power [kW], (c) EP according to ship power [kW], (d) GWP according to ship age [Year], (e) AP according to ship age [Year], (f) EP according to ship age [Year].

7.4.2. Comparison of fuel cells

Figure 7-4 shows the results of comparative analysis across the fuel cell types under the same conditions as discussed in the section 7.4.1. where LNG is assumed to be the original source of energy for fuel cells instead of pure hydrogen.

Figure 7-4(a) to Figure 7-4(c) illustrate the WTT environmental impacts of LNG as marine fuel. The production pathway encompasses from raw material extraction, pipeline supply, liquefaction, transportation to distribution onboard. Since the same amounts of fuel are assumed to be supplied to the fuel cells, all the results are identical in GWP, AP and EP.

Figure 7-4(d) to Figure 7-4(f) show the TTW environmental impacts of using LNG as fuel for onboard fuel cells. In Figure 7-4(d), PEMFC produces the greatest level of GHG emissions, compared to the other two types. For an instance of a vessel with 4,000 kW power, PEMFC, MCFC and SOFC produce about 1.0×10^6 kg CO_2 eq., 5.7×10^5 kg CO_2 eq. and 5.3×10^5 kg CO_2 eq. respectively. On the other hand, in Figure 7-4(e) and Figure 7-4(f), PEMFC as well as SOFC emit near-zero emission whereas MCFC preserves some emissions. Therefore, SOFC is determined to be the greenest fuel cell type in TTW.

However, from an overall life cycle point of view, these results imply that the WTT values are too large relative to the TTW values, so all results are nearly identical in the WTW. As shown in Figure 7-4(g) to Figure 7-4(i), all results are same regardless of fuel cell type. In other words, if LNG is directly used for fuel cells, it can be seen that the LNG WTT phase accounts for the dominant proportion of the entire life cycle of the energy.

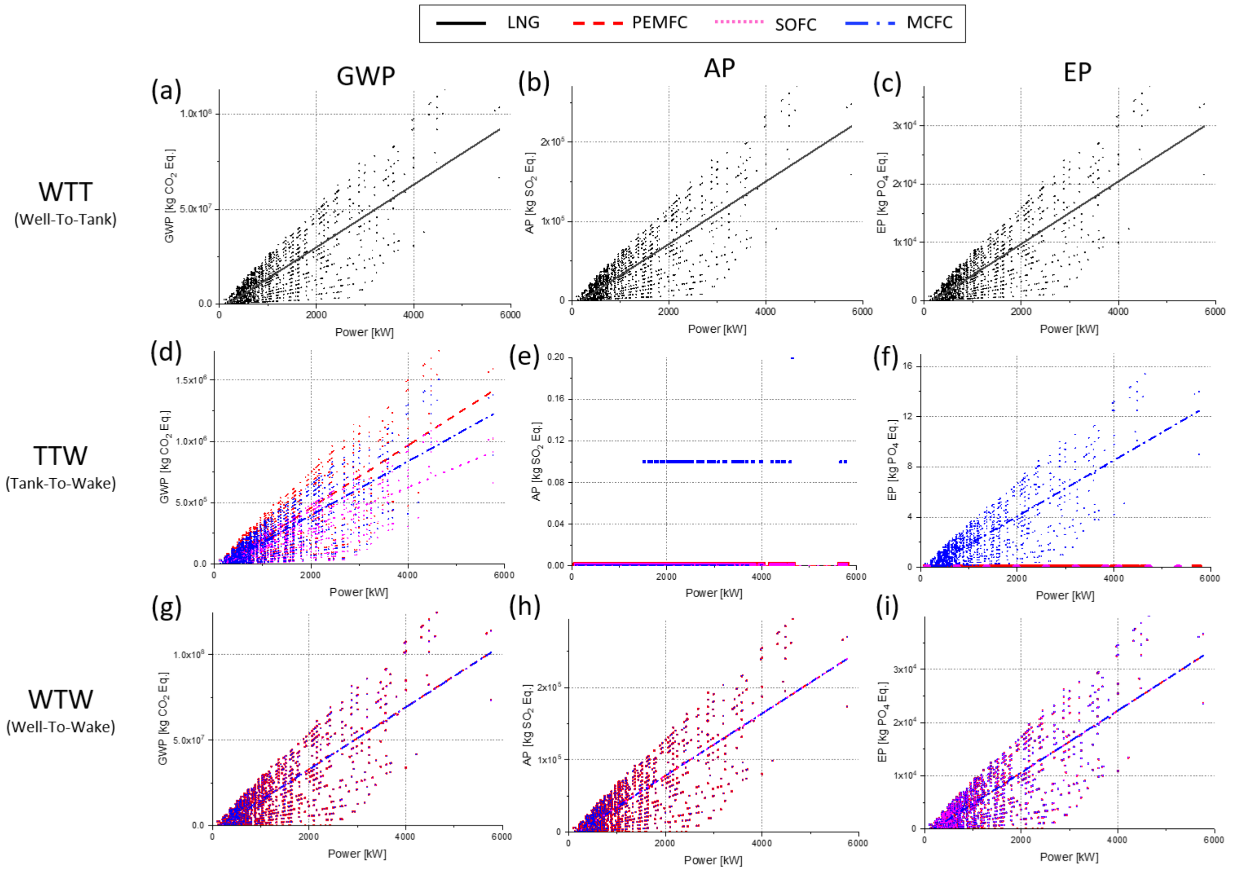

Figure 7-4. Results of comparison of fuel cell types through parametric trend LCA describing environmental impacts according to power [kW]: Lifespan of a ship is 20 years, WTW environmental impacts which are GWP, AP and EP trends (PEMFC – Red dash line, SOFC - Pink dot line, MCFC - Blue dash dot line, LNG - Black solid line), (a) WTT, GWP according to ship power [kW], (b) WTT, AP according to ship power [kW], (c) WTT, EP according to ship power [kW], (d) TTW, GWP according to ship power [kW], (e) TTW, AP according to ship power [kW], (f) TTW, EP according to ship power [kW], (g) WTW, GWP according to ship power [kW], (h) WTW, AP according to ship power [kW], (i) WTW, EP according to ship power [kW].

7.4.3. Comparison with conventional fuels according to maximum and minimum pathways

Further to the comparative analysis across the hydrogen and the fuel cells in the previous sections 7.4.1 and 7.4.2, the underlying task still remains to confirm whether hydrogen fuel cells are ultimately cleaner than conventional oil products.

Figure 7-5(a) to Figure 7-5(c) compare the general trends of environmental impacts of fuel cells to those of diesel ships and LNG fuelled ships (they are identical ships to hydrogen fuelled ships, but propulsion means as dissimilar) at maximum pathway. It is worth noting that, as shown in the Figure 7-5(a), the hydrogen from coal gasification is found to have higher GWP impacts compared to other production methods even worse than diesel and LNG. For example, at 4,000 kW, SMR hydrogen emits 1.7×10^8 kg CO_2 eq. while LNG emits 1.6×10^8 kg CO_2 eq.

SMR hydrogen can be confirmed better in reducing emissions than diesel propulsion from a GWP perspective while appears to be no better than LNG propulsion. However, from the point of view of AP and EP, this method can guarantee much cleaner shipping than conventional fuels as with cracked and electrolytic hydrogen.

Cracking and electrolysis are found as the best hydrogen production methods in terms of GWP, AP and EP. While coal gas hydrogenation and SMR hydrogen tend to significantly increase environmental impacts as with the increase in ship power but cracking and electrolysis remain relatively unchanged.

Figure 7-5(d) to Figure 7-5(f) show the environmental impacts in the minimum pathway of hydrogen production. The differences between coal gasification and SMR hydrogen in the maximum and minimum pathways are particularly noteworthy. According to Figure 7-5(a) and Figure 7-5(d), in terms of GWP, coal gasification is almost kept at the greatest GWP value. However, in terms of AP, Figure 7-5(b) and Figure 7-5(e) show that the method could be a better option than LNG fuel. For a vessel with 4,000 kW power, the hydrogen from coal gasification could emit approximately 2.0×10^6 kg SO_2 eq. in the maximum pathway while emitting about 0.2×10^6 kg SO_2 eq. in the minimum pathway.

Like coal gasification hydrogen, the environmental impacts of SMR hydrogen also vary greatly depending on the maximum and minimum pathways (see Figure 7-5(a) & Figure 7-5(d)). Although SMR hydrogen is less green than LNG propulsion in the maximum pathway, it can be viewed as an eco-friendly option than LNG propulsion in the minimum pathway. In GWP, the eco-friendliness of SMR hydrogen was different depending on the production pathway, whereas AP and EP showed that SMR hydrogen is a very eco-friendly hydrogen production method as much as electrolysis hydrogen in both the maximum and minimum pathways.

As mentioned earlier, since more than 90% of the hydrogen production all over the world is grey hydrogen produced from fossil fuels, there are still many obstacles in achieving a sustainable society with green hydrogen. This research discovers that hydrogen fuel cell has such a possibility to reduce significant emissions. It is worth noting that even SMR hydrogen could be eco-friendlier than LNG and diesel propulsion systems in the case of minimum pathway. However, it is still released some emissions comparing with electrolysis hydrogen. This could not be perfect answer for green shipping goal but could be bridge fuel for LNG and diesel for the time being. Therefore, while studying how to minimize emission when producing grey hydrogen, if green hydrogen infrastructure is established faster and cheaper, it is expected to achieve remarkable eco-friendliness than existing fossil fuels such as LNG and diesel.

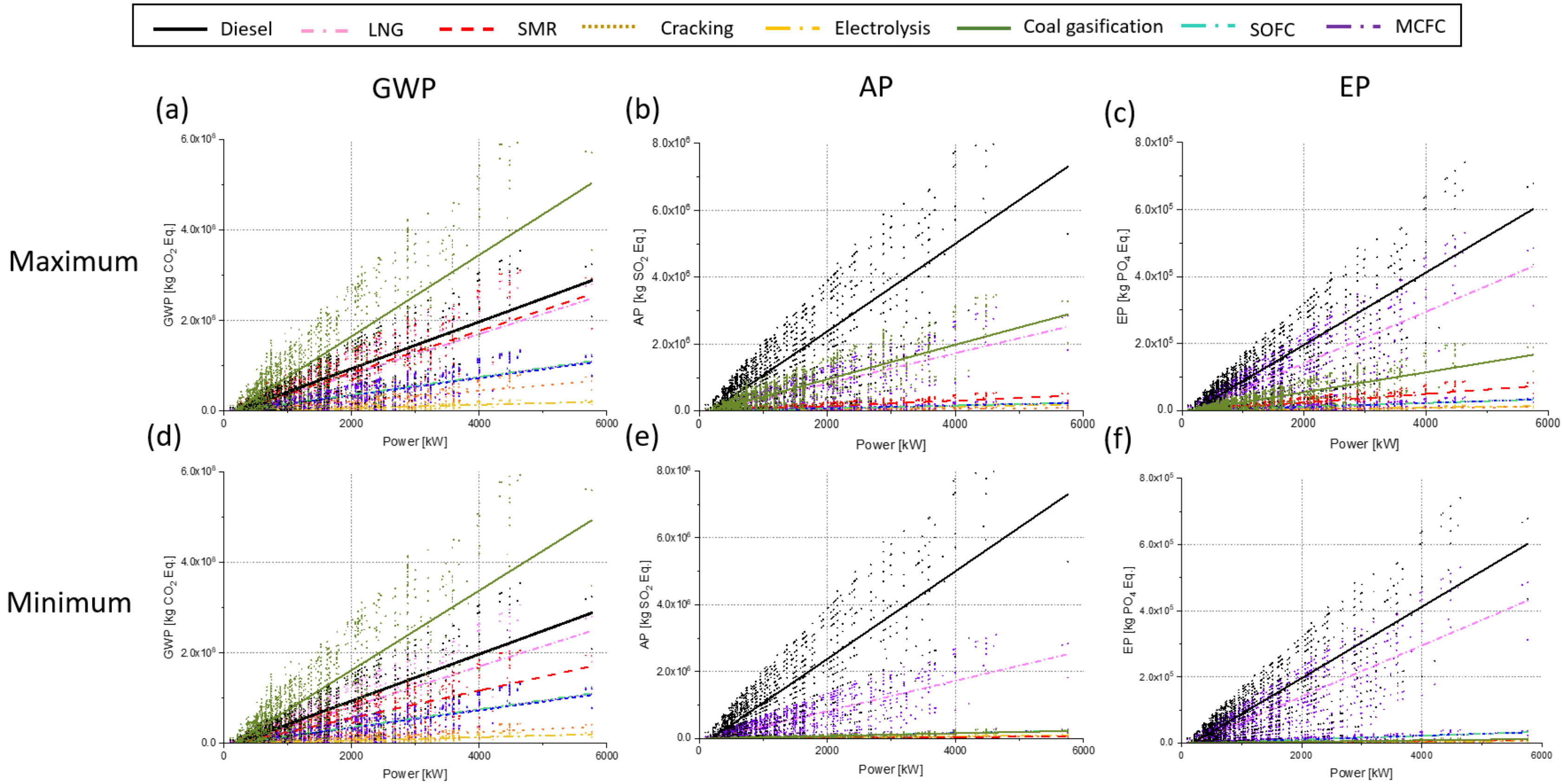

Figure 7-5. Results of comparison of Maximum pathway and Minimum pathway through parametric trend LCA describing environmental impacts according to power [kW]: Lifespan of a ship is 20 years, WTW environmental impacts which are GWP, AP and EP trends (Diesel propulsion – Black solid line, LNG propulsion – Pink short dash dot line, SMR - Red dash line, Cracking - Orange dot line, Electrolysis – Yellow dash dot line, Coal gasification – Green solid line, SOFC using LNG as fuel – Blue short dash line, MCFC using LNG as fuel – Violet short dot line), (a) Maximum, GWP according to ship power [kW], (b) Maximum, AP according to ship power [kW], (c) Maximum, EP according to ship power [kW], (d) Minimum, GWP according to ship power [kW], (e) Minimum, AP according to ship power [kW], (f) Minimum, EP according to ship power [kW].

7.4.4. Comparison of fuel and propulsion types statistically

Figure 7-6 shows whether the environmental impact of previous studies is an appropriate result from a statistical point of view. In Figure 7-6(a), the order from largest to smallest would be: coal gasification hydrogen, diesel, SMR hydrogen, LNG, and the rest of hydrogen production types.

For example, Figure 7-6(a) shows coal gasification with 0.8×10^8 kg CO_2 eq., diesel propulsion with 0.4×10^8 kg CO_2 eq., SMR with 0.35×10^8 kg CO_2 eq. and LNG propulsion with 0.3×10^8 kg CO_2 eq. on average. On the other hand, diesel propulsion was the highest in AP, followed by coal gasification and LNG propulsion. Same as AP, diesel propulsion was the highest in EP, but LNG propulsion showed a wider distribution than coal gasification. In conclusion, the results from a statistical point of view also show similar patterns to the previous analyses.

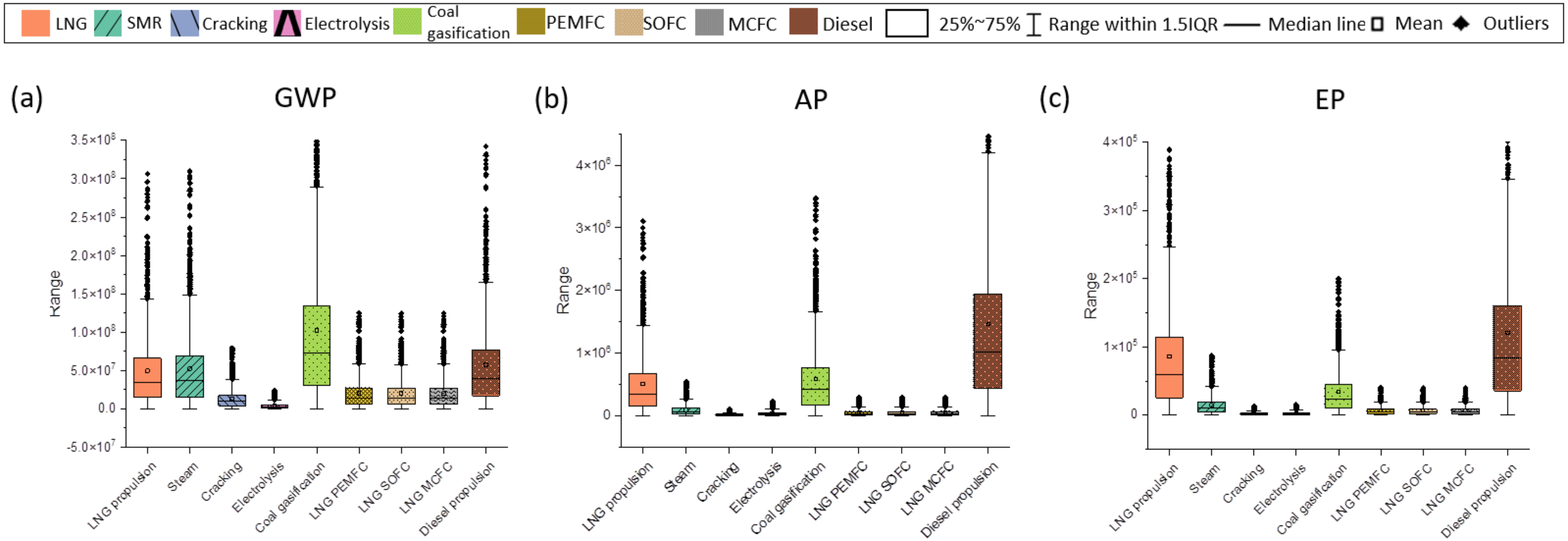

Figure 7-6. Box plot chart results according to fuel & propulsion types.

7.5. Concluding remarks

This chapter aims to answer whether hydrogen fuel cells can truly be a green solution as a propulsion system in the shipping industries from a life cycle perspective. PT-LCA was adopted on around 2,000 ships presently engaged in international and domestic services. The lifecycle environmental impacts of various hydrogen production methods were evaluated, including steam methane reforming, coal gasification, methanol cracking, and electrolysis via wind energy. The performance of three representative types of fuel cell systems, proton exchange membrane fuel, molten carbonate fuel cell, and solid oxide fuel cell were taken into account. The steam methane reforming and coal gasification processes were found to have the greatest environmental consequences across their life cycles. However, this study points out that depending on the production pathways, steam methane reforming could make better lifecycle performance than conventional diesel or LNG products. Additionally, when using LNG as the primary fuel source for fuel cells, it was found that the LNG upstream phase would produce about 100 times more emissions than the downstream phase. The research findings were summarized and condensed into a form of lifetime environmental equations which enable us to understand/evaluate the quantified correlations between holistic environmental impacts of fuel cells and ship characteristics. The research findings are expected to assist stakeholders in making informed decisions, while also providing an insight into near-future regulatory frameworks and policy making for a green hydrogen maritime economy.

8. DISCUSSION & CONCLUSIONS

8.1. Introduction

This chapter presents the comprehensive results of the PhD thesis. Section 8.2. presents the novelty of this research. The main conclusions of this project are discussed in Section 8.3. and finally, the limitations of this study and recommendations for future work are given in Section 8.4.

8.2. Conclusions

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

1) To cope with the growing climate crisis and air pollution, eco-friendly evaluation of the entire fleet in terms of life cycle for alternative fuels and systems for ships is required.

2) Many LCA studies currently applied to ships are focused on case scenario studies, which has a limitation that it cannot be applied to different cases. This limitation causes additional time and money to be consumed in order to provide the results desired by various stakeholders, and it is difficult to reflect the policy to be applied to the general ship as a whole.

3) From the case study for scrubber systems in chapter 5, closed-loop scrubbers are revealed more environmentally friendly than open-loop scrubbers in terms of GWP and AP, whereas the opposite trend is found in EP. It could be equally applied when adopting hybrid scrubber systems. In addition, it was determined whether there was a correlation between ship basic information and the environmental impacts of alternative fuels and systems. As a result, it was found that ship age and power were closely related key parameters, whereas gross tonnage had no significant relationship.

4) From the case study for LNG fuel in chapter 6, it can be further inferred that LNG fuel can be a proper option as a bridge fuel as long as the Well-To-Tank stage is optimally managed. Also, Tank-To-Wake stage generally produces two times more GWPs than Well-To-Tank one. In terms of AP and EP the difference climbs up to about ten times. In other words, the optimal Well-To-Tank would be a key aspect to achieving green shipping. In addition, The PT-LCA showed that even with the same fuel and system, the general environmental assessment can vary greatly depending on how it is produced and consumed. This makes it possible to quantitatively calculate, compare and analyze how fuels are produced and consumed in a more environmentally friendly way.

5) From the case study for hydrogen fuel cells in chapter 7, all hydrogen fuel cells except for coal gasification hydrogen fuel cells were confirmed to reduce all environmental potentials which are GWP, AP and EP comparing with LNG and diesel in the case of the minimum pathway.

6) Through PT-LCA, which conducts LCA for the entire fleet at the same time, time-consuming and repetitive conventional LCA work can be reduced by quickly and easily evaluating which alternative fuels and systems are more eco-friendly according to the age and power of the vessel. The fact that this methodology allows LCA results to be obtained by anyone who does not know LCA, or environmental assessment methods has proven to be the greatest asset of this project.

7) PT-LCA was developed to evaluate the eco-friendliness of future alternative fuels and systems for ships from a holistic point of view. It has proven to be an effective tool for reducing emissions and developing rules or guidelines for alternative fuels or systems. It can be widely utilized and highly believed that the proposed LCA method will also reveal its strengths and weaknesses as future marine fuels.

8.3. Novelty of research

Since the results of previous studies that only focused on the environmental evaluation of a specific ship or system are difficult to apply to other ships, it is not possible to ultimately give a meaningful answer on whether the research object is beneficial. This lack of consistency and scalability has limitations that cannot be applied to marine policies or guidelines.

Thereby, the novelty of the work done on this project lies in establishing and demonstrating how the ultimate eco-friendliness can be investigated by developing an enhanced environmental assessment technique, extending a variety of marine fuels and systems to the applicable to all ships.

It is also noted that this project outcome is significant, as providing the wrong solution to comply with stricter marine environmental regulations along with the Global 2050 target could lead to potential catastrophe in the near future.

In addition, this project developed PT-LCA, an improved environmental assessment method to overcome the limitations of existing LCA practices and applied it to a wide range of marine vessels currently engaged in international voyages. It has been verified as a tool that can be applied to various marine fuels and systems by deriving benefits or damages in the form of functional equations. The equations derived here provide the most accessible format for predicting life cycle emissions from the use of alternative marine fuels and systems.

In other words, the PT-LCA enabled us to encapsulate all the complex and inconsistent information regarding the environmental performance of diverse marine fuels and systems into simple equations which can be expressed as correlations between inputs (ship particular) and outcomes (environmental impacts). This format of outcomes would be helpful to easily understand whether using these fuels and systems are an ultimately better option without any knowledge of LCA, which is known to be inaccessible to marine researchers. In fact, it will be a useful tool for a quick comparison - though hugely extensive analysis is condensed behind it - between the engine types according to different ship characteristics.

All of the above, the contributions of this project to the field can be summarized as below.

• Proposal and demonstration of the excellence of an enhanced LCA methodology to overcome the current assessment challenges and limitations posed on the existing maritime environmental equations and conventional LCA approaches.

• New environmental equations, which encapsulate all the details and technical complexity behind, are useful for estimating the life cycle impacts of all alternative marine fuels and systems in a more relevant and approachable way. Thus, it is highly believed that they contribute to remedying a fundamental challenge inherent in LCA process, while at the same time contributing to making it accessible to anyone interested in evaluating environmental impacts of using alternative marine fuels without requiring expert assistant. It also suggests a credible way to facilitate the use of LCA for a wider range of marine applications.

• Demystifying the life cycle environmental benefits / harms of using future marine fuels and systems by offering clear and quantitative guidance on what the conditions, the marine vessels can benefit from these fuels and systems and what circumstances they cannot. In fact, research findings add new knowledge to the marine industry, helping to rectify unconditional trust of alternatives as a cleaner marine energy source and enhancing proper decision-making for future international policies.

• Presenting the potential power of the new LCA approach which implies great benefits of its functionalities applicable to investigating and answering the various industrial questions for economic, environmental, safety challenges, etc.

8.4. Recommendations for future research

Those equations driven from the PT-LCA have both strengths and weaknesses of descriptive statistics which exist to simplify and generalize certain phenomenon or observation. As a result, there is still a limit to introducing linear regression that indicates a single relation between the input and the output, which inevitably leads to the deviation to some extent. Therefore, the proposed formula can cause some loss of existing information by simplifying and generalizing the existing detailed information, and since it is reliable with R-squared with a range of consistency of 60%-80% in linear regression, rather than being used as a perfect metric to estimate a ship's life cycle environmental impact, it should be used to identify trends in the entire fleet (See Appendix A & B). To improve the reliability, the proposed equations may be necessary to be upgraded with polynomial equations that can consider the impacts of various inputs on the outputs at the same time. Also, because PT-LCA is performed based on the existing LCA results, it is affected by the existing LCA results and the range of data. For example, if the existing LCA was performed only in a specific area, it is desirable to separately perform the LCA in the case of another area to perform PT-LCA. In addition, if the existing LCA research is not performed or if PT-LCA is performed only with a very small amount of research, the quality of the research analysis result is highly likely to be lowered. Therefore, in order to perform PT-LCA, a large amount of data and existing LCA research results are required.

In this project, results were obtained by applying PT-LCA to three alternative fuels and systems for ships: scrubber system, LNG fueleld ships, and hydrogen fuel cells. However, there are still many options for alternative marine fuels, including biofuels, ammonia, etc. Therefore, the next research task will be to show the results of PT-LCA for other fuels and systems that are not covered in this project.

8.5. Concluding remarks

In this chapter, conclusions, novelty of the study, and recommendations for future research are made based on the results of this paper. The developed method is an LCA-based methodology to achieve green shipping, which has conducted comparative analysis of various marine fuels and systems and suggests that it will be applied to more diverse studies in the future.

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APPENDIX A

Table A 1 WTW Maximum pathway environmental impact trends (1. Bulk, 2. Container, 3. LNG carrier, 4. Ro-Ro).

	Equation	Residual Sum of Squares	Pearson's r	R-Square (COD)	Adj. R-Square
(a) LS-HPDF $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 141488.7 \times \mathcal{X} - 2.0E8$ 2. $\mathcal{Y} = 117895.7 \times \mathcal{X} - 9.9E7$ 3. $\mathcal{Y} = 155249.4 \times \mathcal{X} - 9.2E8$ 4. $\mathcal{Y} = 133441.8 \times \mathcal{X} - 3.2E8$	2.9E20 1.6E21 4.9E20 2.5E20	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(b) LS-HPDF $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 1436.1 \times \mathcal{X} - 2.0E6$ 2. $\mathcal{Y} = 1196.6 \times \mathcal{X} - 1.0E6$ 3. $\mathcal{Y} = 1575.8 \times \mathcal{X} - 9.3E6$ 4. $\mathcal{Y} = 1354.4 \times \mathcal{X} - 3.2E6$	3.0E16 1.6E17 5.0E16 2.6E16	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(c) LS-HPDF $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 245.2 \times \mathcal{X} - 353642.0$ 2. $\mathcal{Y} = 204.3 \times \mathcal{X} - 172902.3$ 3. $\mathcal{Y} = 269.1 \times \mathcal{X} - 1596787.3$ 4. $\mathcal{Y} = 231.3 \times \mathcal{X} - 558147.0$	8.9E14 4.8E15 1.4E15 7.6E14	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(d) LS-LPDF $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 169074.0 \times \mathcal{X} - 2.4E8$ 2. $\mathcal{Y} = 140881.1 \times \mathcal{X} - 1.1E8$ 3. $\mathcal{Y} = 185517.4 \times \mathcal{X} - 1.1E9$ 4. $\mathcal{Y} = 159458.2 \times \mathcal{X} - 3.8E8$	4.2E20 2.3E21 7.0E20 3.6E20	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(e) LS-LPDF $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 579.6 \times \mathcal{X} - 835837.4$ 2. $\mathcal{Y} = 483.0 \times \mathcal{X} - 408656.9$ 3. $\mathcal{Y} = 636.0 \times \mathcal{X} - 3774027.1$ 4. $\mathcal{Y} = 546.6 \times \mathcal{X} - 1319187.5$	5.0E15 2.7E16 8.2E15 4.2E15	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(f) LS-LPDF $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 93.8 \times \mathcal{X} - 135383.0$ 2. $\mathcal{Y} = 78.2 \times \mathcal{X} - 66191.3$ 3. $\mathcal{Y} = 103.0 \times \mathcal{X} - 611290.3$	1.3E14 7.1E14 2.1E14	0.77582 0.87331 0.81527	0.60189 0.76267 0.66467	0.60169 0.76261 0.66401

	4. $\mathcal{Y} = 88.5 \times \mathcal{X} - 213672.7$	1.1E14	0.82797	0.68553	0.68528
(g) MS-LPDF $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 189860.5 \times \mathcal{X} - 2.7E8$ 2. $\mathcal{Y} = 158201.6 \times \mathcal{X} - 1.3E8$ 3. $\mathcal{Y} = 208325.6 \times \mathcal{X} - 1.2E9$ 4. $\mathcal{Y} = 179062.5 \times \mathcal{X} - 4.3E8$	5.3E20 2.9E21 8.8E20 4.5E20	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(h) MS-LPDF $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 440.9 \times \mathcal{X} - 6.3E5$ 2. $\mathcal{Y} = 367.4 \times \mathcal{X} - 3.1E5$ 3. $\mathcal{Y} = 483.8 \times \mathcal{X} - 2.8E6$ 4. $\mathcal{Y} = 415.8 \times \mathcal{X} - 1.0E6$	2.9E15 1.5E16 4.7E15 2.4E15	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(i) MS-LPDF $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 68.4 \times \mathcal{X} - 9.8E4$ 2. $\mathcal{Y} = 57.0 \times \mathcal{X} - 4.8E4$ 3. $\mathcal{Y} = 75.0 \times \mathcal{X} - 4.4E5$ 4. $\mathcal{Y} = 64.5 \times \mathcal{X} - 1.5E5$	6.9E13 3.8E14 1.1E14 5.9E13	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(j) LSD $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 163889.0 \times \mathcal{X} - 2.3E8$ 2. $\mathcal{Y} = 136560.8 \times \mathcal{X} - 1.1E8$ 3. $\mathcal{Y} = 179828.2 \times \mathcal{X} - 1.0E9$ 4. $\mathcal{Y} = 154568.1 \times \mathcal{X} - 3.7E8$	4.0E20 2.1E21 6.6E20 3.4E20	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(k) LSD $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 4159.2 \times \mathcal{X} - 5.9E6$ 2. $\mathcal{Y} = 3465.6 \times \mathcal{X} - 2.9E6$ 3. $\mathcal{Y} = 4563.7 \times \mathcal{X} - 2.7E7$ 4. $\mathcal{Y} = 3922.6 \times \mathcal{X} - 9.4E6$	2.5E17 1.4E18 4.2E17 2.1E17	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(l) LSD $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 342.5 \times \mathcal{X} - 4.9E5$ 2. $\mathcal{Y} = 285.4 \times \mathcal{X} - 2.4E5$ 3. $\mathcal{Y} = 375.8 \times \mathcal{X} - 2.2E6$ 4. $\mathcal{Y} = 323.0 \times \mathcal{X} - 7.7E5$	1.7E15 9.5E15 2.8E15 1.4E15	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(m)LS-HPDF (SCR) $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 141488.7 \times \mathcal{X} - 1.8E8$ 2. $\mathcal{Y} = 117895.7 \times \mathcal{X} - 8.3E7$ 3. $\mathcal{Y} = 155249.4 \times \mathcal{X} - 9.0E8$ 4. $\mathcal{Y} = 133441.8 \times \mathcal{X} - 3.0E8$	2.9E20 1.6E21 4.9E20 2.5E20	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(n) LS-HPDF (SCR) $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 267.6 \times \mathcal{X} + 5.3E5$ 2. $\mathcal{Y} = 223.0 \times \mathcal{X} + 7.3E5$ 3. $\mathcal{Y} = 293.6 \times \mathcal{X} - 8.2E5$	1.0E15 5.8E15 1.7E15	0.77582 0.87331 0.81527	0.60189 0.76267 0.66467	0.60169 0.76261 0.66401

	4. $\mathcal{Y} = 252.4 \times \mathcal{X} + 3.1E5$	9.0E14	0.82797	0.68553	0.68528
(o) LS-HPDF (SCR) $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 28.2 \times \mathcal{X} + 1.0E5$ 2. $\mathcal{Y} = 23.5 \times \mathcal{X} + 1.2E5$ 3. $\mathcal{Y} = 30.9 \times \mathcal{X} - 3.4E4$ 4. $\mathcal{Y} = 26.6 \times \mathcal{X} + 8.5E4$	1.1E13 6.4E13 1.9E13 1.0E13	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528

Table A 2 WTW Minimum pathway environmental impact trends (1. Bulk, 2. Container, 3. LNG carrier, 4. Ro-Ro).

	Equation	Residual Sum of Squares	Pearson's r	R-Square (COD)	Adj. R-Square
(a) LS-HPDF $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 102642.0 \times \mathcal{X} - 1.4E8$ 2. $\mathcal{Y} = 85526.6 \times \mathcal{X} - 7.2E7$ 3. $\mathcal{Y} = 112624.5 \times \mathcal{X} - 6.6E8$ 4. $\mathcal{Y} = 96804.4 \times \mathcal{X} - 2.3E8$	1.5E20 8.5E20 2.5E20 1.3E20	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(b) LS-HPDF $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 1321.7 \times \mathcal{X} - 1.9E6$ 2. $\mathcal{Y} = 1101.3 \times \mathcal{X} - 9.3E5$ 3. $\mathcal{Y} = 1450.2 \times \mathcal{X} - 8.6E6$ 4. $\mathcal{Y} = 1246.5 \times \mathcal{X} - 3.0E6$	2.6E16 1.4E17 4.3E16 2.2E16	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(c) LS-HPDF $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 229.9 \times \mathcal{X} - 3.3E5$ 2. $\mathcal{Y} = 191.6 \times \mathcal{X} - 1.6E5$ 3. $\mathcal{Y} = 252.3 \times \mathcal{X} - 1.4E6$ 4. $\mathcal{Y} = 216.8 \times \mathcal{X} - 5.2E5$	7.9E14 4.2E15 1.3E15 6.7E14	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(d) LS-LPDF $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 126782.0 \times \mathcal{X} - 1.8E8$ 2. $\mathcal{Y} = 105641.3 \times \mathcal{X} - 8.9E7$ 3. $\mathcal{Y} = 139112.4 \times \mathcal{X}x - 8.2E8$ 4. $\mathcal{Y} = 119571.5 \times \mathcal{X} - 2.8E8$	2.4E20 1.3E21 3.9E20 2.0E20	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(e) LS-LPDF $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 455.0 \times \mathcal{X} - 6.5E5$ 2. $\mathcal{Y} = 379.2 \times \mathcal{X} - 3.2E5$ 3. $\mathcal{Y} = 499.3 \times \mathcal{X} - 2.9E6$ 4. $\mathcal{Y} = 429.2 \times \mathcal{X} - 1.0E6$	3.0E15 1.6E16 5.1E15 2.6E15	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528

(f) LS-LPDF $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 77.2 \times \mathcal{X} - 1.1E5$ 2. $\mathcal{Y} = 64.3 \times \mathcal{X} - 5.4E4$ 3. $\mathcal{Y} = 84.7 \times \mathcal{X} - 5.0E5$ 4. $\mathcal{Y} = 72.8 \times \mathcal{X} - 1.7E5$	8.9E13 4.8E14 1.4E14 7.5E13	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(g) MS-LPDF $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 145608.4 \times \mathcal{X} - 2.0E8$ 2. $\mathcal{Y} = 121328.4 \times \mathcal{X} - 1.0E8$ 3. $\mathcal{Y} = 159769.7 \times \mathcal{X} - 9.4E8$ 4. $\mathcal{Y} = 137327.2 \times \mathcal{X} - 3.3E8$	3.1E20 1.7E21 5.2E20 2.6E20	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(h) MS-LPDF $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 310.6 \times \mathcal{X} - 4.4E5$ 2. $\mathcal{Y} = 258.8 \times \mathcal{X} - 2.1E5$ 3. $\mathcal{Y} = 340.8 \times \mathcal{X} - 2.0E6$ 4. $\mathcal{Y} = 292.9 \times \mathcal{X} - 7.0E5$	1.4E15 7.8E15 2.3E15 1.2E15	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(i) MS-LPDF $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 51.0 \times \mathcal{X} - 7.3E4$ 2. $\mathcal{Y} = 42.4 \times \mathcal{X} - 3.5E4$ 3. $\mathcal{Y} = 55.9 \times \mathcal{X} - 3.3E5$ 4. $\mathcal{Y} = 48.1 \times \mathcal{X} - 1.1E5$	3.8E13 2.1E14 6.4E13 3.3E13	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(j) LS-HPDF (SCR) $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 102642.0 \times \mathcal{X} - 1.3E8$ 2. $\mathcal{Y} = 85526.6 \times \mathcal{X} - 5.6E7$ 3. $\mathcal{Y} = 112624.5 \times \mathcal{X} - 6.5E8$ 4. $\mathcal{Y} = 96804.4 \times \mathcal{X} - 2.1E8$	1.5E20 8.5E20 2.5E20 1.3E20	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(k) LS-HPDF (SCR) $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 153.2 \times \mathcal{X} + 6.9E5$ 2. $\mathcal{Y} = 127.6 \times \mathcal{X} + 8.1E5$ 3. $\mathcal{Y} = 168.1 \times \mathcal{X} - 7.8E4$ 4. $\mathcal{Y} = 144.5 \times \mathcal{X} + 5.7E5$	3.5E14 1.9E15 5.7E14 2.9E14	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528
(l) LS-HPDF (SCR) $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 12.9 \times \mathcal{X} + 1.3E5$ 2. $\mathcal{Y} = 10.8 \times \mathcal{X} + 1.4E5$ 3. $\mathcal{Y} = 14.2 \times \mathcal{X} + 6.5E4$ 4. $\mathcal{Y} = 12.2 \times \mathcal{X} + 1.2E5$	2.5E12 1.3E13 4.1E12 2.1E12	0.77582 0.87331 0.81527 0.82797	0.60189 0.76267 0.66467 0.68553	0.60169 0.76261 0.66401 0.68528

Table A 3 WTT & TTW maximum pathway environmental impact trends (1. WTT, 2. TTW).

	Equation	Residual Sum of Squares	Pearson's r	R-Square (COD)	Adj. R-Square
(a) LS-HPDF $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$1. \mathcal{Y} = 52280.2 \times \mathcal{X} - 7.5E7$ $2. \mathcal{Y} = 89208.4 \times \mathcal{X} - 1.2E8$	4.0E19 1.1E20	0.77582 0.77582	0.60189 0.60189	0.60169 0.60169
(b) LS-HPDF $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$1. \mathcal{Y} = 125.1 \times \mathcal{X} - 1.8E5$ $2. \mathcal{Y} = 1310.9 \times \mathcal{X} - 1.8E6$	2.3E14 2.5E16	0.77582 0.77582	0.60189 0.60189	0.60169 0.60169
(c) LS-HPDF $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$1. \mathcal{Y} = 17.0 \times \mathcal{X} - 2.4E4$ $2. \mathcal{Y} = 228.2 \times \mathcal{X} - 3.2E5$	4.3E12 7.7E14	0.77582 0.77582	0.60189 0.60189	0.60169 0.60169
(d) LS-LPDF $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$1. \mathcal{Y} = 56916.7 \times \mathcal{X} - 8.2E7$ $2. \mathcal{Y} = 112157.2 \times \mathcal{X} - 1.6E8$	4.8E19 1.8E20	0.77582 0.77582	0.60189 0.60189	0.60169 0.60169
(e) LS-LPDF $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$1. \mathcal{Y} = 136.2 \times \mathcal{X} - 1.9E5$ $2. \mathcal{Y} = 443.3 \times \mathcal{X} - 6.3E5$	2.7E14 2.9E15	0.77582 0.77582	0.60189 0.60189	0.60169 0.60169
(f) LS-LPDF $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$1. \mathcal{Y} = 18.5 \times \mathcal{X} - 2.6E4$ $2. \mathcal{Y} = 75.3 \times \mathcal{X} - 1.0E5$	5.1E12 9.3E-17	0.77582 0.77582	0.60189 0.60189	0.60169 0.60169
(g) MS-LPDF $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$1. \mathcal{Y} = 59554.7 \times \mathcal{X} - 8.5E7$ $2. \mathcal{Y} = 130305.7 \times \mathcal{X} - 1.8E8$	5.3E19 2.5E20	0.77582 0.77582	0.60189 0.60189	0.60169 0.60169
(h) MS-LPDF $\mathcal{Y} = AP$	$1. \mathcal{Y} = 142.6 \times \mathcal{X} - 2.0E5$ $2. \mathcal{Y} = 298.3 \times \mathcal{X} - 4.3E5$	3.0E14 1.3E15	0.77582 0.77582	0.60189 0.60189	0.60169 0.60169

$\mathcal{X} = Vessel\ power$					
(i) MS-LPDF $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 19.3 \times \mathcal{X} - 2.7E4$ 2. $\mathcal{Y} = 49.0 \times \mathcal{X} - 7.0E4$	5.6E12 3.5E13	0.77582 0.77582	0.60189 0.60189	0.60169 0.60169
(j) LS-HPDF (SCR) $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 52280.2 \times \mathcal{X} - 6.4E7$ 2. $\mathcal{Y} = 89150.5 \times \mathcal{X} - 1.2E8$	4.0E19 1.1E20	0.77582 0.77582	0.60189 0.60189	0.60169 0.60169
(k) LS-HPDF (SCR) $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 125.1 \times \mathcal{X} - 8.1E4$ 2. $\mathcal{Y} = 142.4 \times \mathcal{X} - 6.1E5$	2.3E14 3.0E14	0.77582 0.77582	0.60189 0.60189	0.60169 0.60169
(l) LS-HPDF (SCR) $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	1. $\mathcal{Y} = 17.0 \times \mathcal{X} - 1.9E4$ 2. $\mathcal{Y} = 11.2 \times \mathcal{X} - 1.2E5$	4.3E12 1.8E12	0.77582 0.77582	0.60189 0.60189	0.60169 0.60169

APPENDIX B

Table B 1 LNG & Diesel Maximum pathway environmental impact trends.

	Equation	Residual Sum of Squares	Pearson's r	R-Square (COD)	Adj. R-Square
(p) LNG WTT $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 16477.8 \times \mathcal{X} - 3.0E6$	2.54E17	0.78464	0.61566	0.61546
(q) LNG WTT $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 39.4 \times \mathcal{X} - 7.2\mathrm{E}3$	1.45E12	0.78464	0.61566	0.61546
(r) LNG WTT $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 5.3 \times \mathcal{X} - 9.8E2$	2.69E10	0.78464	0.61566	0.61546
(s) LNG TTW $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 28116.9 \times \mathcal{X} - 5.1E6$	7.39E17	0.78464	0.61566	0.61546
(t) LNG TTW $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 413.1 \times \mathcal{X} - 7.6E4$	1.59E14	0.78464	0.61566	0.61546
(u) LNG TTW $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 71.9 \times \mathcal{X} - 1.3E4$	4.83E12	0.78464	0.61566	0.61546
(v) LNG WTW $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 44594.7 \times \mathcal{X} - 8.2E6$	1.86E18	0.78464	0.61566	0.61546
(w) LNG WTW $\mathcal{Y} = AP$	$\mathcal{Y} = 452.6 \times \mathcal{X} - 8.3E4$	1.91E14	0.78464	0.61566	0.61546

$\mathcal{X} = Vessel\ power$					
(x) LNG WTW $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 77.3 \times \mathcal{X} - 1.4E4$	5.58E12	0.78464	0.61566	0.61546
(y) Diesel WTW $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 51654.8 \times \mathcal{X} - 9.5E6$	2.49E18	0.78464	0.61566	0.61546
(z) Diesel WTW $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 1310.9 \times \mathcal{X} - 2.4E5$	1.61E15	0.78464	0.61566	0.61546
(aa) Diesel WTW $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 107.9 \times \mathcal{X} - 1.9E4$	1.09E13	0.78464	0.61566	0.61546

Table B 2 Hydrogen fuel cell Maximum pathway environmental impact trends.

	Equation	Residual Sum of Squares	Pearson's r	R-Square (COD)	Adj. R-Square
(a) PEMFC WTW $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 19844.5 \times \mathcal{X} - 3.6E6$	3.69E17	0.7841	0.61481	0.61461
(b) PEMFC WTW $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 42.9 \times \mathcal{X} - 7.9E3$	1.72E12	0.78464	0.61566	0.61546
(c) PEMFC WTW $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 5.8 \times \mathcal{X} - 1.0E3$	3.19E10	0.78464	0.61566	0.61546
(d) SOFC WTW	$\mathcal{Y} = 19172.2 \times \mathcal{X} - 3.5E6$	3.44E17	0.78428	0.6151	0.6149

$\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$					
(e) SOFC WTW $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 42.9 \times \mathcal{X} - 7.9E3$	1.72E12	0.78464	0.61566	0.61546
(f) SOFC WTW $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 5.8 \times \mathcal{X} - 1.0E3$	3.19E10	0.78464	0.61566	0.61546
(g) MCFC WTW $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 19588.2 \times \mathcal{X} - 3.5E6$	3.60E17	0.78417	0.61492	0.61472
(h) MCFC WTW $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 42.9 \times \mathcal{X} - 7.9E3$	1.72E12	0.78464	0.61566	0.61546
(i) MCFC WTW $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 5.8 \times \mathcal{X} - 1.0E3$	3.21E10	0.78463	0.61564	0.61544

Table B 3 Hydrogen methodologies Maximum pathway environmental impact trends.

	Equation	Residual Sum of Squares	Pearson's r	R-Square (COD)	Adj. R-Square
(a) SMR WTT $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 46150.2 \times \mathcal{X} - 7.4E6$	2.09E18	0.777	0.60373	0.60352
(b) SMR WTT $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 80.5 \times \mathcal{X} - 1.3E4$	6.38E12	0.777	0.60373	0.60352

(c) SMR WTT $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 12.9 \times \mathcal{X} - 2.0E3$	1.64E11	0.777	0.60373	0.60352
(d) Cracking WTT $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 11811.2 \times \mathcal{X} - 1.9E6$	1.37E17	0.777	0.60373	0.60352
(e) Cracking WTT $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 16.4 \times \mathcal{X} - 2.6E3$	2.66E11	0.777	0.60373	0.60352
(f) Cracking WTT $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 1.9 \times \mathcal{X} - 3.1E2$	3.65E9	0.777	0.60373	0.60352
(g) Electrolysis WTT $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 3628.8 \times \mathcal{X} - 5.8E5$	1.29E16	0.777	0.60373	0.60352
(h) Electrolysis WTT $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 34.8 \times \mathcal{X} - 5.6E3$	1.19E12	0.777	0.60373	0.60352
(i) Electrolysis WTT $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 2.2 \times \mathcal{X} - 3.6E2$	5.06E9	0.777	0.60373	0.60352
(j) Coal gasification WTT $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 89884.7 \times \mathcal{X} - 1.4E7$	7.94E18	0.777	0.60373	0.60352
(k) Coal gasification WTT $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 516.2 \times \mathcal{X} - 8.3E4$	2.62E14	0.777	0.60373	0.60352
(l) Coal gasification WTT $\mathcal{Y} = EP$	$\mathcal{Y} = 29.7 \times \mathcal{X} - 4.8E3$	8.67E11	0.777	0.60373	0.60352

$\mathcal{X} = Vessel\ power$					

Table B 4 Hydrogen methodologies Minimum pathway environmental impact trends.

	Equation	Residual Sum of Squares	Pearson's r	R-Square (COD)	Adj. R-Square
(a) SMR WTT $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 30456.8 \times \mathcal{X} - 4.9E6$	9.11E17	0.777	0.60373	0.60352
(b) SMR WTT $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 11.2 \times \mathcal{X} - 1.8E3$	1.24E11	0.777	0.60373	0.60352
(c) SMR WTT $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 1.9 \times \mathcal{X} - 3.1E2$	3.74E9	0.777	0.60373	0.60352
(d) Cracking WTT $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 6499.9 \times \mathcal{X} - 1.0E6$	4.15E16	0.777	0.60373	0.60352
(e) Cracking WTT $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 13.0 \times \mathcal{X} - 2.1E3$	1.67E11	0.777	0.60373	0.60352
(f) Cracking WTT $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 1.0 \times \mathcal{X} - 1.7E2$	1.12E9	0.777	0.60373	0.60352
(g) Electrolysis WTT $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 3570.1 \times \mathcal{X} - 5.7E5$	1.25E16	0.777	0.60373	0.60352
(h) Electrolysis WTT	$\mathcal{Y} = 18.3 \times \mathcal{X} - 2.9E3$	3.32E11	0.777	0.60373	0.60352

$\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$					
(i) Electrolysis WTT $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 1.0 \times \mathcal{X} - 1.7E2$	1.12E9	0.777	0.60373	0.60352
(j) Coal gasification WTT $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 88027.6 \times \mathcal{X} - 1.4E7$	7.61E18	0.777	0.60373	0.60352
(k) Coal gasification WTT $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 40.8 \times \mathcal{X} - 6.6E3$	1.64E12	0.777	0.60373	0.60352
(l) Coal gasification WTT $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 2.1 \times \mathcal{X} - 3.4E2$	4.56E9	0.777	0.60373	0.60352

APPENDIX C

Table C 1 Trajectories and overview reference of marine LCA.

Topic	Author(s)	Title
Initial life cycle perspective for shipping	Fet et al. (1996)	Environmental Impacts and Activity Based Costing during Operation of a Platform Supply Vessel
	Johnsen and Fet (1999)	Screening Life Cycle Assessment of M/V Color Festival
	Fet (1998)	ISO 14000 as a Strategic Tool for Shipping and Shipbuilding
	Fet and Sørgård (1998)	Life Cycle Evaluation of Ship Transportation - Development of Methodology and Testing
	Fet et al. (2013)	Systems engineering as a holistic approach to life cycle designs
Ship design, shipbuilding & operation	Hayman, Dogliani, Kvale, and Fet (2000)	Technologies for reduced environmental impact from ships: Ship building, maintenance, and dismantling aspects
	Jivén et al. (2004)	LCA-ship, design tool for energy efficient ships, A life cycle analysis program for ships
	Kameyama, Hiraoka, Sakurai, Naruse, and Tauchi (2005)	Development of LCA Software for Ships and LCI Analysis based on Actual Shipbuilding and Operation
	Kameyama et al. (2007)	Study on Life Cycle Impact Assessment for Ships
	Tincelin, Mermier, Pierson, Pelerin, and Jouanne (2010)	A life cycle approach to shipbuilding and ship operation
	Tincelin et al. (2010)	Environmental impact of ship hull repair
	Carvalho, Antão, and Soares (2011)	Modelling of environmental impacts of ship dismantling
	Tchertchian, Yvars, and Millet (2013)	Benefits and limits of a Constraint Satisfaction Problem/Life Cycle Assessment approach for the eco-design of complex systems: a case applied to a hybrid passenger ferry
	Koch, Blanco-Davis, and Zhou (2013)	Analysis of Economic and Environmental Performance of Retrofits using Simulation
	Rahman et al. (2016)	Life cycle assessment of steel in the ship recycling industry in Bangladesh
	Jang, Jang, Jeong, and Cho (2021)	Comparative life cycle assessment of marine insulation materials

Alternative propulsion systems	Altmann, Weindorf, and Weinberger (2004)	Life cycle analysis results of fuel cell ships
	Alkaner and Zhou (2006)	A comparative study on life cycle analysis of molten carbon fuel cells and diesel engines for marine application
	Strazza et al. (2010)	Comparative LCA of methanol-fuelled SOFCs as auxiliary power systems on-board ships
Marine eco-friendly technologies	Basurko and Mesbahi (2014)	Methodology for the sustainability assessment of marine technologies
	Blanco-Davis and Zhou (2014)	LCA as a tool to aid in the selection of retrofitting alternatives
	Blanco-Davis, Del Castillo, and Zhou (2014)	Fouling release coating application as an environmentally efficient retrofit: a case study of a ferry type ship
	Zhou and Davis (2014)	Energy efficiency optimisation, through the use of an absorption cooling system onboard fishing vessels
	J Ling-Chin, Heidrich, and Roskilly (2016)	Life cycle assessment - from analysing methodology development to introducing an LCA framework for marine photovoltaic systems
	Janie Ling-Chin and Roskilly (2016a)	A comparative life cycle assessment of marine power systems
	Janie Ling-Chin and Roskilly (2016b)	Investigating the implications of a new-build hybrid power system for Roll-on/Roll-off cargo ships from a sustainability perspective
	Blanco-Davis and Zhou (2016)	Life cycle assessment as a complementary utility to regulatory measures of shipping energy efficiency
	H. Wang, Oguz, Jeong, and Zhou (2017)	Optimisation of operational modes of short-route ferry: a life cycle assessment case study
	Jeong et al. (2018)	An effective framework for life cycle and cost assessment for marine vessels aiming to select optimal propulsion systems
	Jeong, Jeon, Kim, Kim, and Zhou (2020)	Evaluation of the lifecycle environmental benefits of full battery powered ships: Comparative analysis of marine diesel and electricity
	Winebrake, Corbett, and Meyer (2007)	Energy use and emissions from marine vessels: A total fuel life cycle approach.
	Corbett and Winebrake (2008)	Emissions tradeoffs among alternative marine fuels: Total fuel cycle analysis of residual oil, marine gas oil, and marine diesel oil

Marine alternative fuels	Verbeek et al. (2011)	Environmental and economic aspects of using LNG as a fuel for shipping in the Netherlands
	S. Bengtsson et al. (2011)	A comparative life cycle assessment of marine fuels liquefied natural gas and three other fossil fuels
	S. Bengtsson et al. (2012)	Environmental assessment of two pathways towards the use of biofuels in shipping
	Ryste (2012)	Screening LCA of GHG emissions related to LNG as ship fuel, Department of Marine Technology
	Øberg (2013)	Life Cycle Assessment of Fuel Choices for Marine Vessels
	Baldi et al. (2013)	The influence of propulsion system design on the carbon footprint of different marine fuels
	Laugen (2013)	An environmental life cycle assessment of LNG and HFO as marine fuels
	Lowell et al. (2013)	Assessment of the fuels cycle impacts of liquified natural gas as used in international shipping
	S. K. Bengtsson et al. (2014)	Fuels for short sea shipping: A comparative assessment with focus on environmental impact
	Brynolf et al. (2014)	Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol, and bio-methanol
	Brynolf (2014)	Environmental Assessment of Present and Future Marine Fuels
	Paul Gilbert et al. (2018)	Assessment of full life-cycle air emissions of alternative shipping fuels
	El-Houjeiri et al. (2019)	LCA of greenhouse gas emissions from marine fuels
	Kesieme et al. (2019)	Attributional LCA of biofuels for shipping: Addressing alternative geographical locations and cultivation systems
	Cepeda et al. (2019)	A review of the use of LNG versus HFO in maritime industry
	S. Hwang, Jeong, Jung, Kim, and Zhou (2019)	LCA of LNG fuelled vessel in domestic services
	Sharafian et al. (2019)	Natural gas as a ship fuel: assessment of greenhouse gas and air pollutant reduction potential
	Jang et al. (2020)	Development of Parametric Trend Life Cycle Assessment for marine SOx reduction scrubber system
	Jang, Jeong, Zhou, Ha, and Nam (2021)	Demystifying the lifecycle environmental benefits and harms of LNG as marine fuel

Table C 2 Overview reference of Well-To-Tank (WTT) LNG emission (Jang, Jeong, et al., 2021).

Year	Reference	Geographical boundary	WTT (upstream) LNG Emissions					
			NG extraction or production	NG transport to liquefaction	NG purification & liquefaction	LNG transport to storage	LNG storage and distribution	Total
2011	(Verbeek et al., 2011)	From Qatar to Rotterdam	CO_2 0.7 g/MJ CH_4 0.007 g/MJ	-	CO_2 0.7 g/MJ purification CO_2 4.2 g/MJ liquefaction CH_4 0.04 g/MJ purification & liquefaction	Transported over 1000 km by vessel CO_2 2.5 g/MJ CH_4 0.02 g/MJ	CO_2 0.3 g/MJ Terminal CO_2 0.6 g/MJ Distribution	CO_2 9.0 g/MJ CH_4 1.7 g/MJ
2011	(Verbeek et al., 2011)	From North Sea or Slochteren to Rotterdam	CO_2 0.7 g/MJ CH_4 0.007 g/MJ	CO_2 0.5 g/MJ CH_4 0.001 g/MJ	CO_2 0.7 g/MJ purification CO_2 5.0 g/MJ liquefaction CH_4 0.04 g/MJ purification & liquefaction	-	CO_2 0.6 g/MJ Distribution	CO_2 7.5 g/MJ CH_4 1.4 g/MJ
2011	(Verbeek et al., 2011)	From Siberia to Rotterdam	CO_2 0.7 g/MJ CH_4 0.007 g/MJ	Transported over 7000 km by pipeline CO_2 10.2 g/MJ CH_4 0.19 g/MJ	CO_2 0.7 g/MJ purification CO_2 5.0 g/MJ liquefaction CH_4 0.04 g/MJ purification & liquefaction	-	CO_2 0.6 g/MJ Distribution	CO_2 17.2 g/MJ CH_4 5.9 g/MJ
2014	(Brynolf et al., 2014)	From Norway to Gothenburg	Natural gas production in Norway	-	Assumed the liquefaction plant has an overall efficiency of 93%.	-	Distributed from North Sea to Gothenburg (350 NM) with an LNG tanker with DF engines.	CO_2 8.3 g/MJ CH_4 0.033 g/MJ NOx 0.0095 g/MJ SOx 0.00083 g/MJ
2017	(Tagliaferri, Clift, Lettieri, & Chapman, 2017)	From Qatar to the industrial city of Ras Laffan through wet subsea pipelines.	CO_4 2.3 g/MJ	CO_2 5.9 g/MJ	CO_2 5.5 g/MJ	CO_2 6.8 g/MJ	LNG evaporation CO_2 2.4 g/MJ Natural gas distribution at long-distance pipeline CO_2 0.66 g/MJ Natural gas distribution at high pressure to the consumer CO_2 0.41 g/MJ Natural gas distribution at low pressure to the consumer CO_2 0.18 g/MJ	CO_2 24 g/MJ
2019	(Sharafian et al., 2019)	In North American countries (Domestic LNG case)	In North American countries CO_2 9.14 g/MJ CH_4 0.15 g/MJ NOx 0.016 g/MJ	In North American countries CO_2 3.71 g/MJ CH_4 0.03 g/MJ NOx 0.031 g/MJ	In North American countries CO_2 7.67 g/MJ CH_4 0.04 g/MJ NOx 0.008 g/MJ	In North American countries CO_2 1.86 g/MJ CH_4 0.01 g/MJ NOx 0.004 g/MJ SOx 0.0003 g/MJ	In North American countries CO_2 2.87 g/MJ CH_4 0.09 g/MJ NOx 0.001 g/MJ	CO_2 25.25 g/MJ CH_4 0.32 g/MJ NOx 0.059 g/MJ SOx 0.0133 g/MJ

			SOx 0.0106 g/MJ	SOx 0.0006 g/MJ	SOx 0.0016 g/MJ		SOx 0.0001 g/MJ	
2019	(Sharafian et al., 2019)	From North American countries to the other countries (Imported LNG case)	In North American countries CO_2 9.19 g/MJ CH_4 0.15 g/MJ NOx 0.016 g/MJ SOx 0.0106 g/MJ	In North American countries CO_2 3.71 g/MJ CH_4 0.03 g/MJ NOx 0.031 g/MJ SOx 0.0006 g/MJ	In North American countries CO_2 7.67 g/MJ CH_4 0.04 g/MJ NOx 0.008 g/MJ SOx 0.0016 g/MJ	Transported by ships to the other countries CO_2 3.29 g/MJ CH_4 0.01 g/MJ NOx 0.035 g/MJ SOx 0.0102 g/MJ	Distributed by trucks, barges. CO_2 2.88 g/MJ CH_4 0.09 g/MJ NOx 0.001 g/MJ SOx 0.0002 g/MJ	CO_2 26.73 g/MJ CH_4 0.32 g/MJ NOx 0.091 g/MJ SOx 0.0233 g/MJ
2019	(Skone, Cooney, Jamieson, Littlefield, & Marriott, 2014)	From New Orleans to Rotterdam, Netherlands	CO_2 21 kg/MWh Natural gas extraction CO_2 49 kg/MWh Natural gas gathering & boosting CO_2 18 kg/MWh Natural gas processing	CO_2 61 kg/MWh Domestic Pipeline Transport	CO_2 38 kg/MWh Liquefaction	CO_2 28 kg/MWh Tanker/Rail Transport CO_2 4 kg/MWh LNG Regasification	-	CO_2 219 kg/MWh
2019	(Skone et al., 2014)	From Oran, Algeria to Rotterdam, Netherlands	CO_2 66 kg/MWh Natural gas extraction CO_2 48 kg/MWh Natural gas gathering & boosting CO_2 18 kg/MWh Natural gas processing	CO_2 61 kg/MWh Domestic Pipeline Transport	CO_2 39 kg/MWh Liquefaction	CO_2 40 kg/MWh Tanker/Rail Transport CO_2 4 kg/MWh LNG Regasification	-	CO_2 276 kg/MWh
2019	(Skone et al., 2014)	From Yamal, Russia to Rotterdam, Netherlands	CO_2 61 kg/MWh Natural gas extraction CO_2 45 kg/MWh Natural gas gathering & boosting CO_2 17 kg/MWh Natural gas processing	CO_2 166 kg/MWh Domestic Pipeline Transport	-	-	-	CO_2 289 kg/MWh
2019	(Skone et al., 2014)	From New Orleans to Shanghai, China	CO_2 21 kg/MWh Natural gas extraction CO_2 50 kg/MWh Natural gas gathering & boosting CO_2 18 kg/MWh Natural gas processing	CO_2 60 kg/MWh Domestic Pipeline Transport	CO_2 41 kg/MWh Liquefaction	CO_2 76 kg/MWh Tanker/Rail Transport CO_2 4 kg/MWh LNG Regasification	-	CO_2 270 kg/MWh
2019	(Skone et al., 2014)	From Oran, Algeria to Shanghai, China	CO_2 66 kg/MWh Natural gas extraction CO_2 48 kg/MWh Natural gas gathering & boosting	CO_2 61 kg/MWh Domestic Pipeline Transport	CO_2 38 kg/MWh Liquefaction	CO_2 19 kg/MWh Tanker/Rail Transport CO_2 4 kg/MWh LNG Regasification	-	CO_2 254 kg/MWh

			CO_2 18 kg/MWh Natural gas processing					
2019	(Skone et al., 2014)	From Yamal, Russia to Shanghai, China	CO_2 63 kg/MWh Natural gas extraction CO_2 46 kg/MWh Natural gas gathering & boosting CO_2 17 kg/MWh Natural gas processing	CO_2 222 kg/MWh Domestic Pipeline Transport	-	-	-	CO_2 348 kg/MWh
2019	(Schuller, Kupferschmid, Hengstler, & Whitehouse, 2019)	From Algeria, Australia, Indonesia, Malaysia, Nigeria, Norway, Qatar, Trinidad & Tobago and the USA to Europe, North America, Asia Pacific, China, and Middle East	CO_2 6.1 g/MJ		CO_2 9.2 g/MJ	CO_2 2.5 g/MJ	CO_2 0.7 g/MJ	CO_2 18.5 g/MJ
2020	(Pavlenko et al., 2020)	From a mix of conventional (48%) and shale gas (52%) produced in the United States and use the most recent baseline in the GREET model.	Considered	Considered	Considered	Considered	Considered	CO_2 11 g/MJ CH_4 0.3 g/MJ

Table C 3 TTW emissions for proposed LNG fueled propulsion and their efficiency (Sharafian et al., 2019).

		Engine type			
		LNG fueled engines			HFO fueled engine
		MS-LPDF (Stenersen & Thonstad, 2017)	LS-LPDF (Fernández et al., 2017)	LS-HPDF (Sharafian et al., 2019)	LSD (Sharafian et al., 2019)
Engine Efficiency (J/J)		0.44	0.505	0.5	0.5
SFC (g/kWh) (Pavlenko et al., 2020)		149	142.3	130.7	180
SFC (MJ/kWh) (Pavlenko et al., 2020)		7.45	7.12	6.54	7.19
Emission factor					
NOx	g/kWh engine output	1.9	2.68	8.76	11.58
	g/MJ fuel	0.23	0.37	1.22 0.06 (with SCR)	1.61
	g/kg fuel	11.29	18.27	59.13	62.73
CO	g/kWh engine output	1.9	1.9 (Stenersen & Thonstad, 2017)	0.79	0.64
	g/MJ fuel	0.23	0.27	0.11	0.09
	g/kg fuel	11.29	12.95	5.33	3.47
CH_4	g/kWh engine output	6.9	3.3 (Ott et al., 2016)	0.01 (BRYAN Comer et al., 2017)	0.01 (BRYAN Comer et al., 2017)
	g/MJ fuel	0.84	0.46	0.00139	0.0014
	g/kg fuel	40.99	22.5	0.068	0.054
	%	4.1	2.25	0.0068	0.0054
CO_2	g/kWh engine output	444.2	412	446	577
	g/MJ fuel	54.29	57.79	61.95	80.14
	g/kg fuel	2,638.6	2,808.8	3,010.5	3,125.4
SOx	g/kWh engine output	0.17	0.17	0.41	10.29
	g/MJ fuel	0.021	0.024	0.057	1.429
	g/kg fuel	1.01	1.16	2.78	55.74
PM	g/kWh engine output	0.02 (BRYAN Comer et al., 2017)	0.01	0.92 (Stenersen & Thonstad, 2017)	1.42 (BRYAN Comer et al., 2017)
	g/MJ fuel	0.0024	0.0015	0.128	0.1972
	g/kg fuel	0.12	0.068	6.23	7.69

- Lower heating value (LHV) of LNG: 48.6 MJ/kg
- Lower heating value of HFO: 39.0 MJ/kg
- Emission per unit of fuel energy (g/MJ fuel) = 1/3.6 x g/kWh engine output x efficiency engine
- Emissions per mass of fuel (g/kg fuel) = g/MJ fuel x LHV fuel (MJ/kg)