Parametric Trend Life Cycle Assessment for Hydrogen Fuel cell towards Cleaner Shipping

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ABSTRACT

Given the rapidly increasing concern of the climate change, this paper is aimed to answer whether hydrogen fuel cells can truly be a green solution in the shipping sector from a life cycle perspective. To achieve this goal, the parametric trend life cycle assessment which is LCA-based methodology was applied for 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

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processes were found to have the greatest environmental potentials across their lifetime. However, this paper points out that steam methane reforming could make better lifecycle merits than conventional diesel or LNG products, if production pathways are properly proposed. 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 summarised and condensed into a form of lifetime environmental indicators 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.

Keywords: Hydrogen, Fuel cell, Decarbonisation shipping, Parametric Trend Life Cycle Assessment

ABBREVIATIONS and TERMS

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
EP	Eutrophication Potential
GHG	Green House Gases
GUI	Graphic User Interface
GWP	Global Warming Potential
HCl	Hydrogen Chloride
IMO	International Maritime Organization
LCA	Life Cycle Assessment
LSD	Low-speed diesel cycle engine
LS-HPDF	Low-speed high-pressure dual-fuel engine
PEMFC	Proton exchange membrane fuel cell
MCFC	Molten carbonate fuel cell
SOFC	Solid oxide fuel cell
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MCDA	Multiple-Criteria Decision making Analysis
NG	Natural Gas
NOx	Nitrogen Oxides
OLS	Ordinary least squares
PT-LCA	Parametric Trend LCA
PM	Particulate Matters

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
SFC	Specific Fuel Consumptions
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
WTT	Well-To-Tank
WTW	Well-To-Wake

1. Introduction

1.1. Overview

Maritime transport has contributed to producing enormous amount of greenhouse gases and air pollutants to the global environment (Deniz & Zincir, 2016). The International Maritime Organization (IMO) and local governments have responded to such an urgent issue by developing a series of strict environmental regulations to mitigate the effects of global warming and air pollution from shipping activities.

Marine Environment Protection Committee (MEPC) of the IMO has enacted Annex VI regulations 13 and 14 of the International Convention for the Prevention of Ship Pollution (MARPOL), which mandate marine vessels to gradually reduce NOx and SOx emissions (IMO, 2014). 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 (IMO, 2018). Similarly, NOx emission regulations are limited by the engine speed of used and new marine diesel vessels (Van, Ramirez, Rainey, Ristovski, & Brown, 2019). In addition, the IMO has set a target for reducing greenhouse gas (GHG) emissions by at least 50% by 2050 compared to 2008 levels (IMO, 2020). 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.

However, the shipping 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 reflect life cycle perspective. It means that they do not consider the release of other greenhouse gases such as methane and N_2O emissions. Accordingly, environmental assessments and related regulation are inevitably incomplete. It is because only CO_2 factor is considered and many other global warming emissions 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. In a related study, Pavlenko, Comer, Zhou, Clark, and Rutherford (2020) concluded that LNG could not achieve cleaner shipping from a life cycle point of view.

In addition, the fact that the current shipping environmental regulations focus only on operation phase could also be an obstacle to achieving cleaner shipping. For example, focusing only on the process in which the scrubber system is used without considering the construction and scrapping process of the scrubber system, the total emissions from the scrubber will not be reflected in the regulation (Jang et al., 2020).

Currently, life cycle assessment (LCA) is considered as the optimal tool to reflect this status, and the development of LCA-based regulations and guidelines applicable to marine alternative fuels has been required (MEPC73, 2018).

Meanwhile, to comply with stricter regulations and achieve cleaner shipping, hydrogen has been hailed as one of the most promising solutions (Yan et al., 2020). In line with this pattern, the outlook for the hydrogen production market trend is also positive. Fig. 1 shows hydrogen production is expected to continue to increase as ten governments around the world adopt hydrogen strategies (IEA, 2021). To propel ships using hydrogen as fuel, hydrogen fuel cells provide excellent energy efficiency without increasing NOx emissions, so the development of a ship propulsion system using a hydrogen fuel cell has been mainly progressed (Yan et al., 2020). 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).

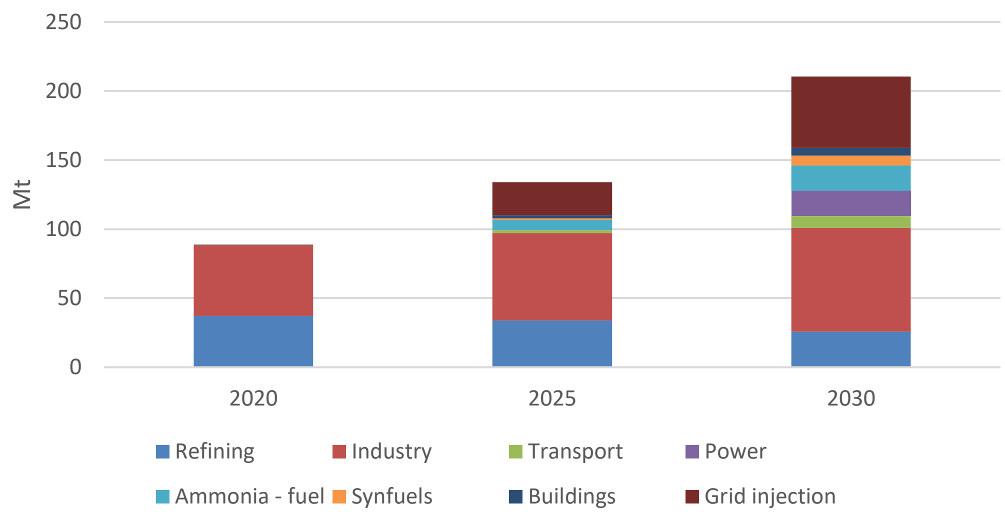

Fig. 1: Global hydrogen demand by sector in the Net zero scenario, 2020-2030 (IEA, 2021).

1.2. Literature review

As interest in hydrogen fuel cells has grown significantly, various studies have been conducted on whether hydrogen fuel cells are greener. 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). Hwang et al. (2020) conducted a comparative LCA relative to the excellence of hydrogen as a marine fuel in comparison 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. For shipping, de-Troya, Álvarez, Fernández-Garrido, and Carral (2016) evaluated the best conditions of fuel cell applications to ships.

Environmental studies on hydrogen production methods as well as hydrogen fuel cells have been actively conducted. 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 life cycle assessment (LCA) for the similar production methods under the European scenarios. Bhandari, Trudewind, and Zapp (2014) conducted a thorough review of 21 past research papers associated with life cycle studies of hydrogen production technologies. With no exception, those studies have commonly pointed out the adequacy of using renewable energy sources - wind, hydro and solar - to reduce emissions.

On the other hand, there are different findings. For example, Noureddine Hajjaji, Pons, Renaudin, and Houas (2013) concluded that biomethane reforming systems was the greenest in terms of GWP, AP, EP, etc. comparing steam reforming, biological methane reforming, and bioethanol-to-hydrogen systems. Li, Yao, Tachega, Ahmed, and Ismaail (2021) rated Cu-Cl thermochemical water-splitting as the greenest technology in terms of GWP and AP among coal gasification, natural gas steam reforming, water electrolysis via wind power and Cu-Cl thermochemical water-splitting.

Hence, the past LCA studies on hydrogen fuel cell can be summarized into that hydrogen would be a cleaner maritime energy source than conventional fossil fuels if produced by electrolysis methods coupled with renewable energies.

The problem, however, is that the results of LCA studies conducted by a few specific case vessels cannot be applied to other vessels. This is because the LCA results for each vessel are different. This issue could cause inconsistency and confusion among various stakeholders. In this regard, it is difficult to directly apply the past LCA results to the guidelines or policies of the shipping industry.

To overcome this limitation, a methodology through regression analysis that can handle the data of entire fleet is required in this paper. Padey, Blanc, Le Boulch, and Xiusheng (2012), a representative study that applied regression analysis to LCA, defined representative wind turbines and then performed regression analysis based on detailed LCA results on representative samples to present a simplified LCA model. In addition, Caduff, Huijbregts, Koehler, Althaus, and Hellweg (2014) applied regression analysis to the result of parameterizing the entire LCA object to reveal the relationship between the parameters of the LCA object and the environmental impact. However, those studies were subject to demonstration issues on the sampling methods whether the samples in the analysis could represent the whole cases. If not, results from the regression analysis may be not useful for other cases. With the insight from those past research works, a key feature of this study is to offer a standardized guideline on the proper application of regression analysis for LCA.

1.3. Contribution of this paper

In response, as discussed earlier in Section 1.2, an LCA-based general observation methodology is required to be developed to determine the general environmental tendency of whole fleets (rather than a single case ship) with hydrogen fuel cells.

By developing an LCA-based methodology, thousands of LCA results are commonly observed and, through linear regression of the derived results, general relations of the ship characteristics and hydrogen production methods with and the environmental impacts will be determined. The derived general observation will be represented as environmental indicators in the form of a bundle of 1st order single equations. The proposed indicators will be an effective tool that can help diverse stakeholders to communicate easily without knowledge of complex environmental analysis and evaluation. For lawmakers, for example, those indicators 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. The derived indicators can also contribute to shipping environmental guidelines or regulations by offering quantified environmental impact values according to the basic information of a ship such as ship power and age. Thus, these results can be quantitatively evaluated as to which of the hydrogen production methods or various fuel cells are the greenest and most harmful.

To achieve this goal, Section 2 (Method applied) introduces the proposed LCA method that can provide general observation covering the entire fleet than a single vessel. Section 3 (Case Study) discusses the results of the comparative analysis on different types of hydrogen production methods, fuel cell systems and other marine fuels through the methodology introduced in Section 2. Based on the results, the answer to the fundamental question is sought in Section 4 (Discussion). Finally, key findings are highlighted in section 5 (Conclusions).

2. Methodology

This paper is intent to propose Parametric Trend LCA (PT-LCA) which was initially developed and applied to the scrubber system (Jang et al., 2020) and LNG as marine fuel (Jang, Jeong, Zhou, Ha, & Nam, 2021). PT-LCA basically consists of three phases which are goal and scope definition, modelling, and results. The overall structure of PT-LCA is on the same line as the ISO LCA guidelines which consist of goal and scope, LCI, LCIA, and interpretation but tailored for the purpose of this research, whereas the parametric trend analysis has been added to this 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 specific 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 to identify the correlation between each input parameter and emission levels. In the end, a variety of decision-makers would be provided much broader holistic view with more information. Following explanation shows the differences between conventional LCA and PT-LCA and explains in detail how to proceed with PT-LCA.

2.1. Comparison between conventional LCA and PT-LCA

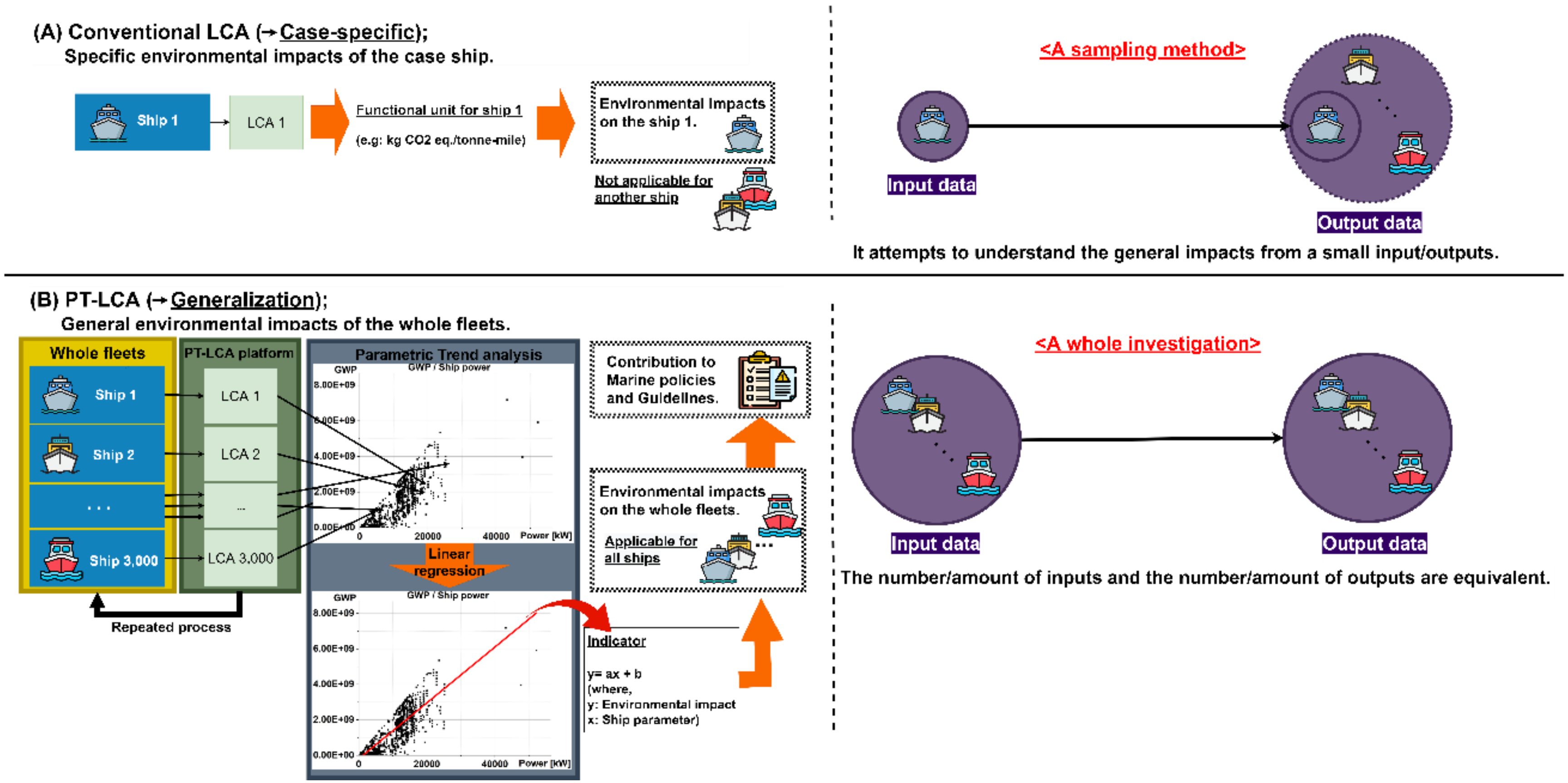

Fig. 2. Comparison between conventional LCA(A) and PT-LCA(B).

Fig. 2 shows the distinction between conventional LCA practices and PT-LCA. In the shipping industry, conventional LCA research have mainly been focused on case studies by selecting one or two case ships. However, as revealed in literature review, those research results have inherent limitations that they cannot be applied to different ships. These limitations inevitably require generalization process through which a piece of simple results is used for the inferencing process to predict the environmental performances of ships in other categories. Overall outcomes from this generalization process are not able to directly be applied for marine environmental policies or guidelines for thousands of ships without a validation process.

Meanwhile, PT-LCA is basically designed based on the ISO LCA guidelines but uses thousands of data for the entire fleet rather than some sample data for one or two case ships. In addition, as the process of the parametric trend analysis is added, PT-LCA results are formed as the tendency of environmental impacts over ship characteristics so that they can be applicable for the entire vessels and directly fed into the international policy. In this phase, the input value was set as the ship's power and the result value was defined as environmental impacts (GWP, AP, EP), so that it can be understood the general relationships between the input and the output. It will be the answer to the question that how much ship power contribute to increasing/decreasing the environmental impacts from the life cycle perspective according to the power of a ship. The following are the specific process of PT-LCA.

2.2. Phase 1. Goal and scope

2.2.1. General database collection

In PT-LCA, the first step basically needs to set the system boundary and assumptions 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 study 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.

2.2.2. Alternative fuel databases

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.

2.2.3. Ship databases

Whereas the existing LCA selects a few ships and analyses 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. Therefore, 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 database collected in the previous step.

2.2.4. The functional unit

The functional unit of PT-LCA is set differently from the conventional LCA. While the existing LCA study is to evaluate the environmental friendliness of a specific object or two objects, the PT-LCA is a method by identifying how the environmental impacts of thousands of objects change according to the input parameters. It is helpful to decision makers and rule makers by not only comparing and analysing their environmental friendliness, but also showing the patterns of environmental friendliness of the entire population. 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/tonne-mile for comparative analysis and applied to actual ships. For this reason, the form of the functional unit of PT-LCA is expressed by a linear function as y=ax+b (where, y is environmental impact, x is basic information of a ship such as power). This simple formula enables to estimate, calculate, and compare environmental impacts with only basic information of the vessel so that it can take over the role of traditional functional units. Above all, the PT-LCA can figure out the amount of change in the environmental characteristics of entire fleets according to the ship basic information, which could not be estimated in the existing LCA. 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 calculation of the power of the ship. As a result, the overall environmental impact for all ships, regardless of ship power, can be predicted and compared to all ships.

2.3. Phase 2. Modelling

In this phase, it is necessary to build a unique PT-LCA platform capable of performing life cycle inventory analysis (LCI) and life cycle impact assessment (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 GUI features and graphics and provides 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 repeatedly thousands of times simultaneously, with thousands of results graphed with the x-axis of the ship's basic information such as 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. The following is a more detailed explanation of how to implement and operate PT-LCA through LabVIEW software.

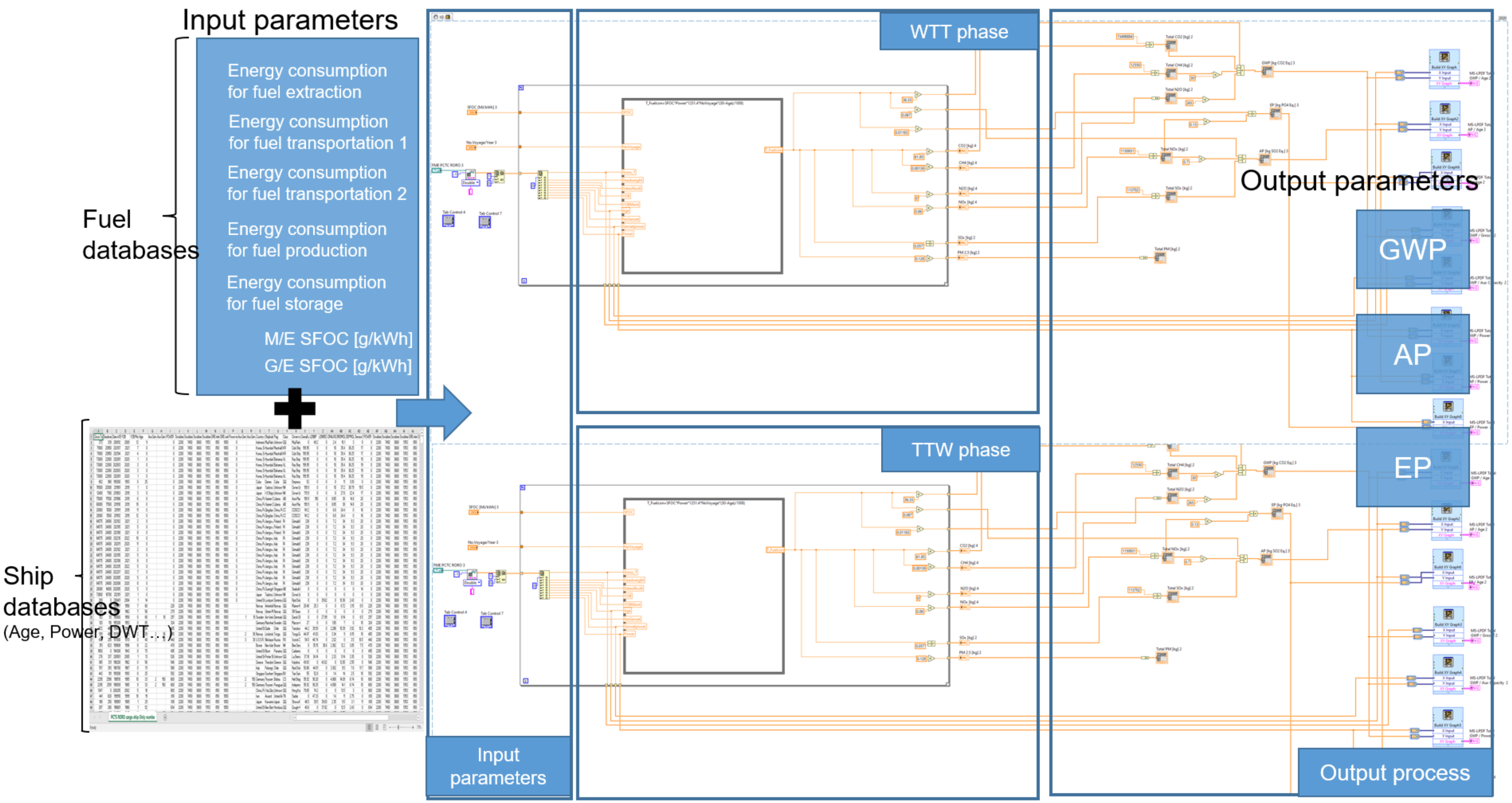

Fig. 3: PT-LCA LabVIEW platform calculation procedure for a fuel (LCI, LCIA phases).

Fig. 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 phase 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 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.

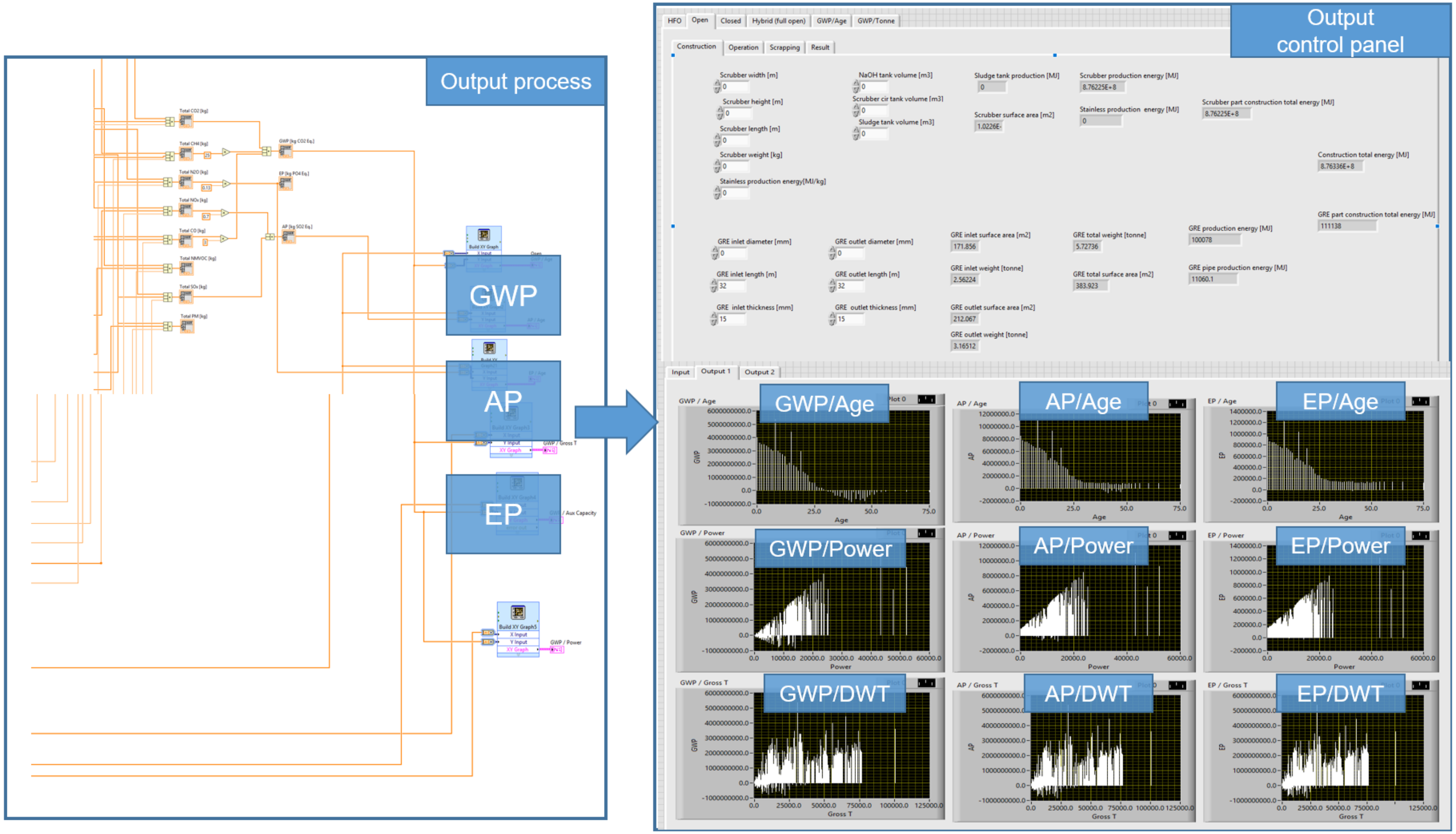

Fig. 4: PT-LCA LabVIEW platform for graphed outputs.

As shown in Fig. 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.

2.4. Phase 3. Results (Interpretation, Parametric trend analysis)

Among the 3 phases of the results stage, the interpretation stage interacts with other stages, reflecting the ISO guideline. Therefore, it is required to check whether phases 1 and 2 are progressing harmoniously and consistently, and this process can be quantitatively evaluated using the correlation coefficient R-squared through regression analysis in the parameter trend analysis stage.

The parameter trend analysis step is to determine the correlation between basic information of the ship and environmental impacts by linear regression of the individual LCA results expressed on the result graphs.

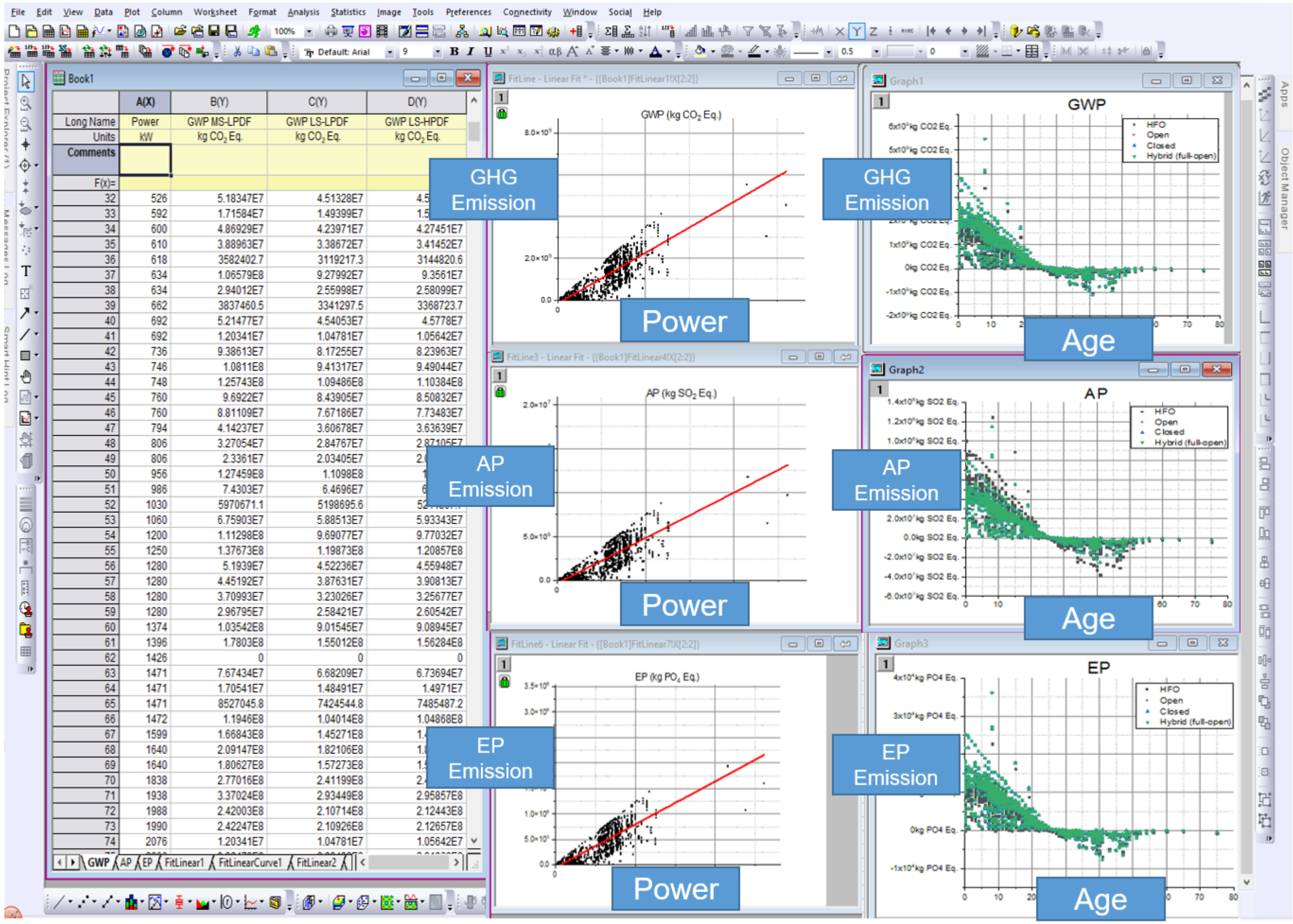

Fig. 5: Example of linear regression process through origin screenshot.

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, **Error! Reference source not found.** 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.

To do so, thousands of vessel environmental impacts database sets computed from the PT-LCA platform in LabVIEW were imported into origin software (OriginLab, Inc., version 2022) and performed with ordinary least squares (OLS) linear regression. The independent variable reflects the correlation of the dependent variables (GWP, AP, EP) with the ship's power. With 95% confidence interval, the intercept (a value) and the slope (b value) are presented.

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 $y = ax + b$. This formula enables to infer how much environmental impacts change according to the power of the ship from the viewpoint of the life cycle; it was revealed by Jang et al. (2020) that the power of a ship has a strong correlation with environmental impacts.

Thus, diverse stakeholders would be able to find out LCA results of the ship easily and quickly with only basic information of the ship, 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.

In terms of 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.

3. Case study

3.1. Phase 1: Goal and scope

3.1.1. General scope

As shown in Fig. 6(a), this paper 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 onboard fuel consumption.

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 (CO2) emissions by 2050. Currently, CO2 (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, Jang, Zhou, & Lee, 2019). Therefore, this paper does not consider the WTW impacts of fuel cell systems.

▪ Lifespan of vessels is assumed to be 20 years without berthing or anchoring.

▪ The functional unit of conventional LCA is to express and compare quantitative environmental evaluations. On the other hand, in the PT-LCA, quantitative environmental evaluation is expressed and compared with the LCA indicators, which are mathematic equations expressing the correlation between ship basic information and environmental impacts.

▪ In the indicator, x value is ship power, and x value must be within the used ship data power value. Meanwhile, y value is environmental impacts which are GWP, AP, and EP. It should also be fit between 60%-80% as an R-squared which is the coefficient of determination in linear regression.

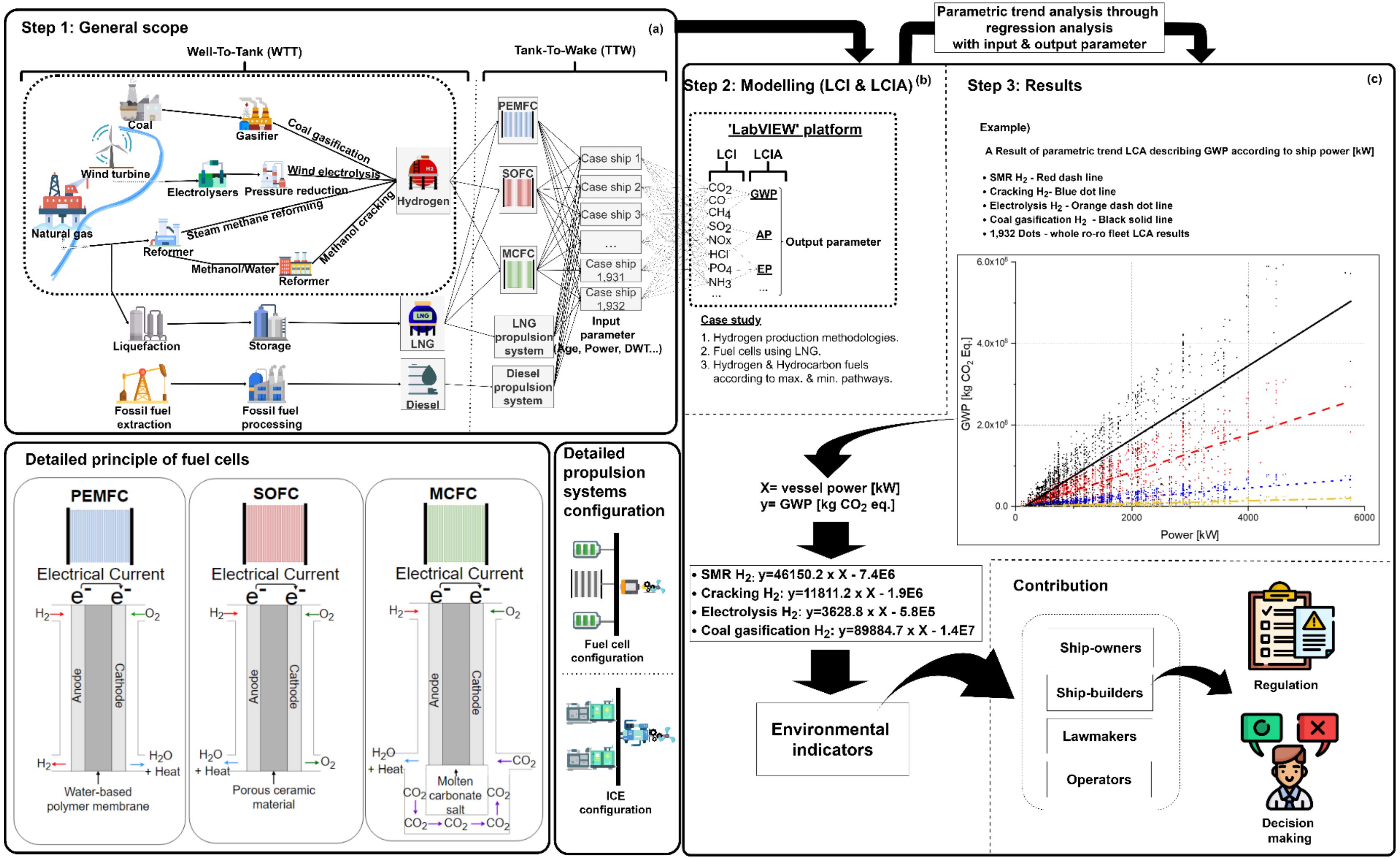

Fig. 6. Overview of hydrogen fuel cell PT-LCA with detailed hydrogen pathway, configurations of related systems.

3.1.1.1. *Hydrogen production*

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. Data collection

3.1.1.2. *Vessel*

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. It is worth mentioning that fuel cell technologies are still at its early stage in the marine industry so that they are not feasible for large vessels engaged in the international voyages. Given this, this paper was focused on the small ships having 500 GT or less. To be specific, Fig. 7 shows the number of ships according to the age, power and dead weight tonnage (DWT) of the ship used in this paper.

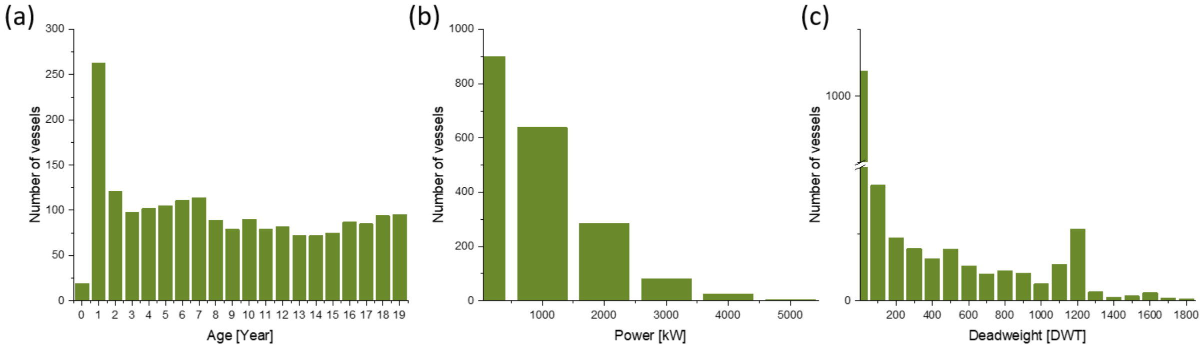

Fig. 7. Distribution chart of vessels database according to major input parameters: (a) vessel numbers according to age (Year), (b) vessel numbers according to power (kW) and (c) vessel numbers according to deadweight (DWT).

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.

3.2. Phase 2: Modelling

As shown in Fig. 6(b), the modelling phase of the PT-LCA incorporates the life cycle inventory (LCI) and life cycle impact assessment (LCIA) phases to design an established platform that can connect with thousands of sample databases simultaneously. This paper is divided into two life stages, WTT and TTW, while tracking the inflow and outflow of representative emissions which are CO_2, CO, CH_4, HCl, NOx, SOx and NMVOC from the life cycle activities associated with fuels (IMO, 2014, 2018).

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

Fig. 6(a) illustrates the WTT pathways of existing LCA studies for the four hydrogen production methods: SMR, cracking, electrolysis, coal gasification.

Table 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 3 presents the results of the estimating the environmental impacts based on Table 1 that indicates the characterization factors for GWP, AP and EP obtained from several LCA results. 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.

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 2. 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 2 LNG & Diesel WTT inventory results (Sharafian, Blomerus, & Mérida, 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}

Table 3 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}	-

3.2.2. 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:

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

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 4 were applied to estimate the environmental impacts when hydrocarbons such as LNGs are used as fuel in fuel cells.

Table 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 5 shows the TTW inventory dataset for LS-HPDF and LSD engine.

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

	LS-HPDF (Diesel, 2012)	LSD (Diesel, 2012)
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} (Comer, Olmer, Mao, Roy, & Rutherford, 2017)	1.40×10^{-3} (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} (Comer et al., 2017)

3.3. Phase 3: Results

3.3.1. Comparison of hydrogen production methods

Fig. 8(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 plotted on 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 6 Total sum of the environmental impacts of WTW hydrogen fuel cell.

	SMR	Cracking	Electrolysis	Coal gasification
GWP [kg CO2 eq.]	1.01E+11	2.59E+10	7.97E+09	1.97E+11
AP [kg SO2 eq.]	1.77E+08	3.61E+07	7.66E+07	1.13E+09
EP [kg PO4 eq.]	2.84E+07	4.23E+06	4.99E+06	6.53E+07

The results in Fig. 8(a), for example, 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 the GWP row of Table 6, that aggregates all the GWP value of each vessel, as shown in Fig. 8(a). The results of the analysis show that when entire fleets in Fig. 8(a) use hydrogen based on fossil fuel, they contribute to aggravating the climate change ten times greater than hydrogen based on renewable energy. Specifically, 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 hydrogen produced by cracking or electrolysis process. 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 Fig. 8(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 Fig. 8(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 Fig. 8(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, Fig. 8(d) – Fig. 8(f) show the trends of the WTW environmental impacts of all types of hydrogen with the case ships. Similar to Fig. 8(a) to Fig. 8(c), Fig. 8(d) to Fig. 8(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 Fig. 8(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.

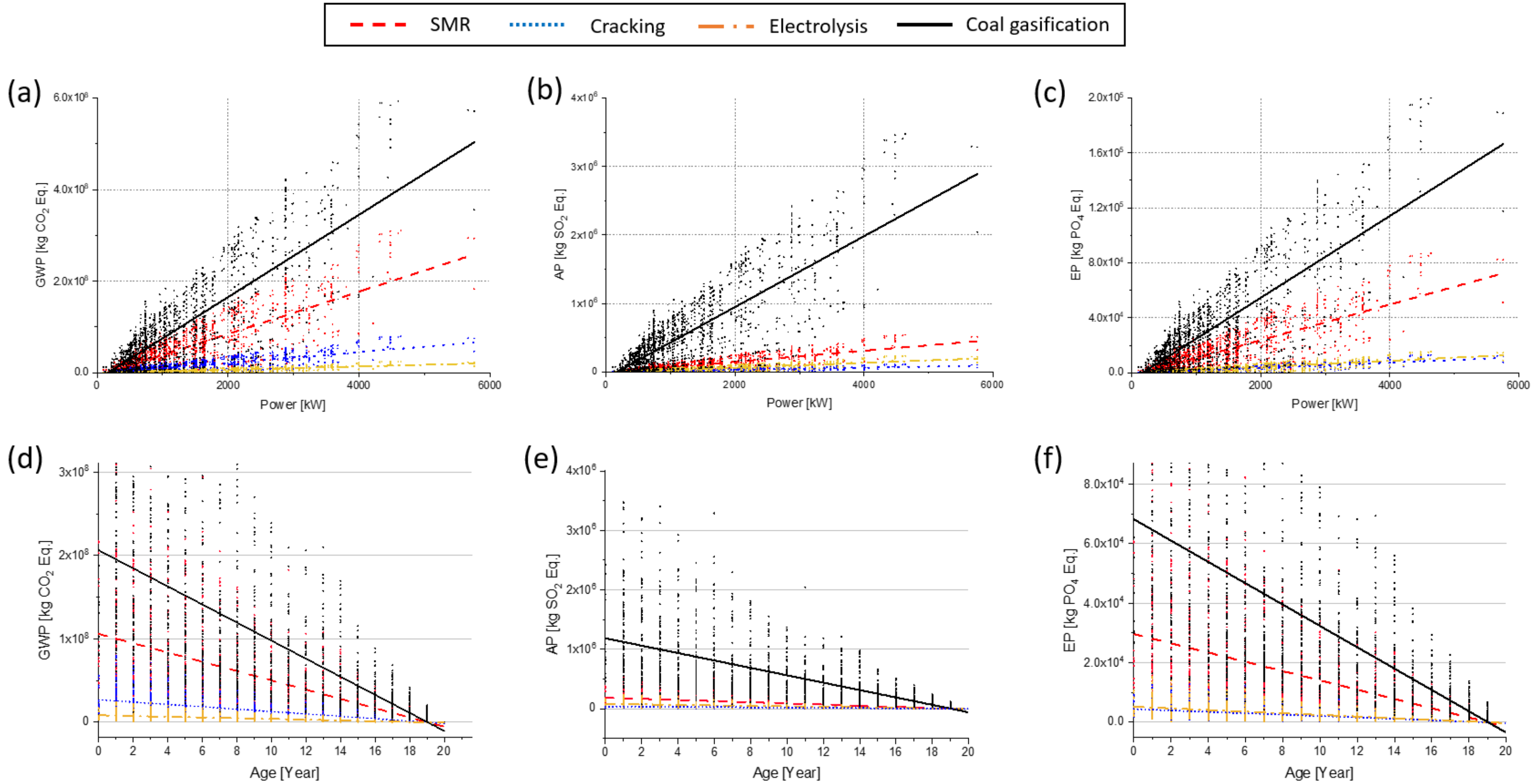

Fig. 8. Results of comparison of hydrogen production methods through parametric trend LCA describing environmental impacts according to power [kW] & age [Year]: Lifespan of a ship is 20 years, WTW environmental impacts which are GWP, AP and EP trends (SMR H_2 – Red dash line, Cracking H_2 - Blue dot 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].

3.3.2. Comparison of fuel cells

Fig. 9 shows the results of comparative analysis across the fuel cell types under the same conditions as discussed in the section 3.3.1. where LNG is assumed to be the original source of energy for fuel cells instead of pure hydrogen.

Fig. 9(a) to Fig. 9(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.

Fig. 9(d) to Fig. 9(f) show the TTW environmental impacts of using LNG as fuel for onboard fuel cells. In Fig. 9(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 Fig. 9(e) and Fig. 9(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 Fig. 9(g) to Fig. 9(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.

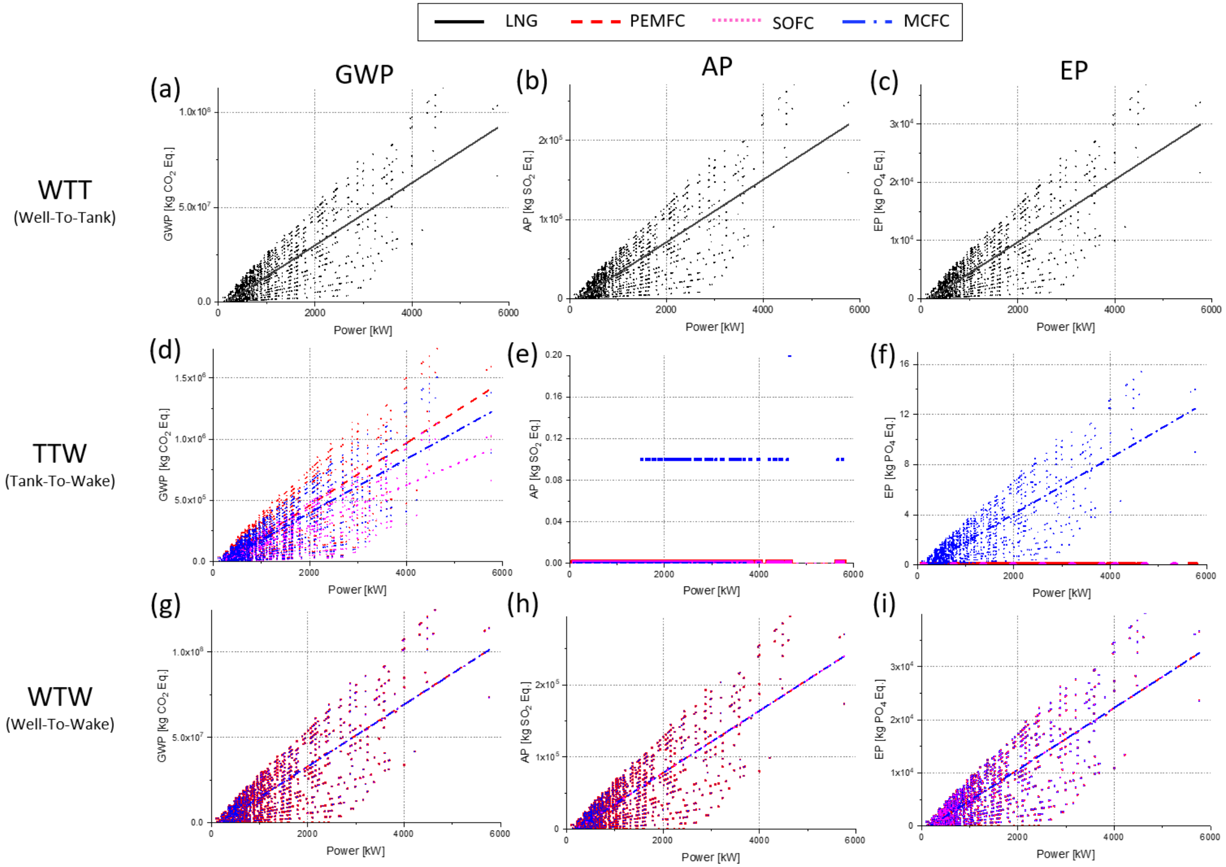

Fig. 9. Results of comparison of fuel cell types through parametric trend LCA describing environmental impacts according to power [kW]: Lifespan of a ship is 20 years, WTW environmental impacts which are GWP, AP and EP trends (PEMFC – Red dash line, SOFC - Pink dot line, MCFC - Blue dash dot line, LNG - 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].

3.3.3. 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 3.3.1 and 3.3.2, the underlying task remains to confirm whether hydrogen fuel cells are ultimately cleaner than conventional oil products.

Fig. 10(a) to Fig. 10(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 Fig. 10(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.

Fig. 10(d) to Fig. 10(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 Fig. 10(a) and Fig. 10(d), in terms of GWP, coal gasification is almost kept at the greatest GWP value. However, in terms of AP, Fig. 10(b) and Fig. 10(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 Fig. 10(a) & Fig. 10(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. Therefore, these research findings provide not only hydrogen based on renewable energy (Green hydrogen), but also hydrogen based on fossil fuel (Grey hydrogen) can be eco-friendly solutions according to hydrogen production pathways.

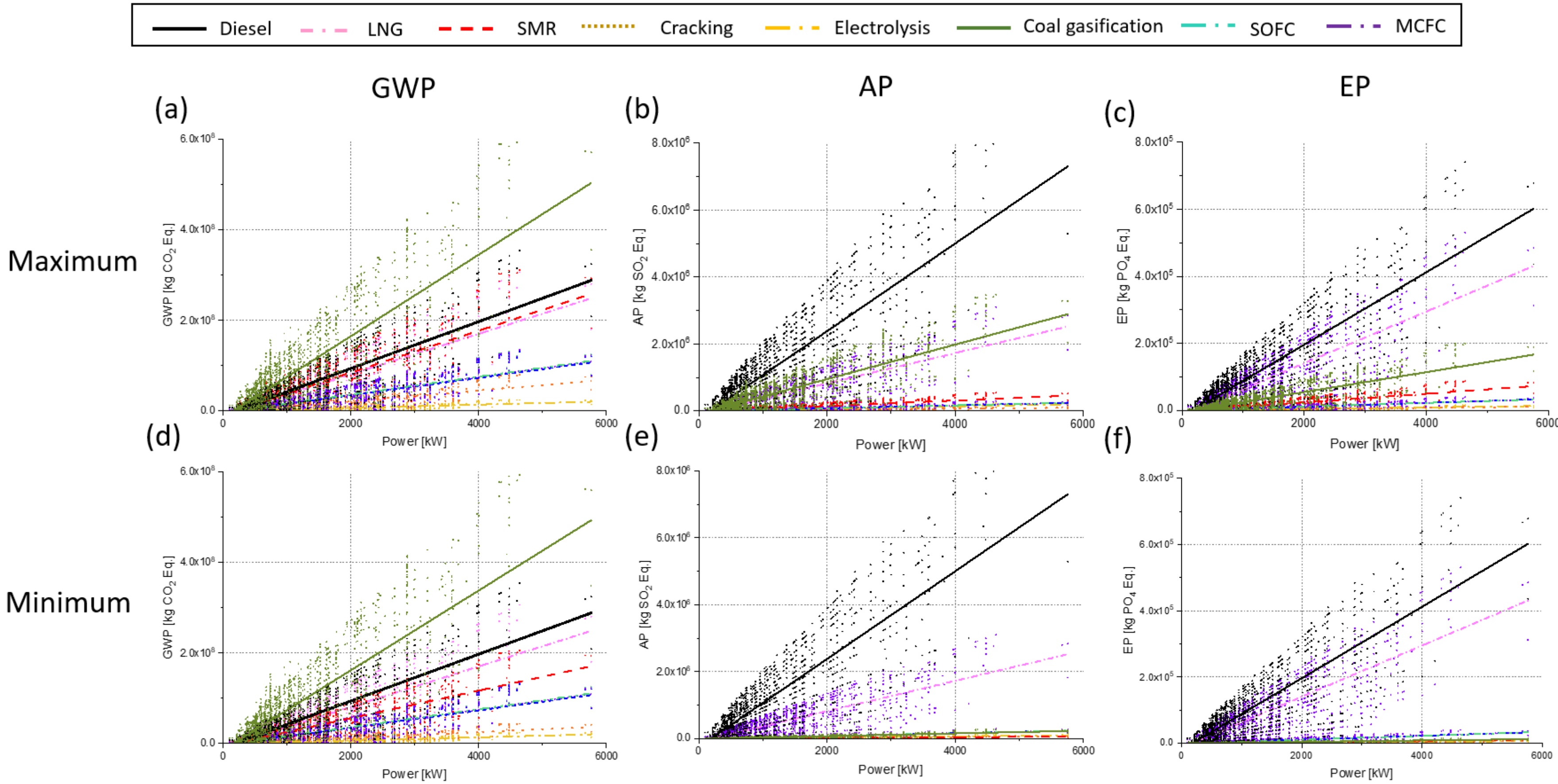

Fig. 10. Results of comparison of Maximum pathway and Minimum pathway through parametric trend LCA describing environmental impacts according to power [kW]: Lifespan of a ship is 20 years, WTW environmental impacts which are GWP, AP and EP trends (Diesel propulsion – Black solid line, LNG propulsion – 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].

3.3.4. Comparison of fuel and propulsion types statistically

Fig. 11 shows whether the environmental impact of previous studies is results from a statistical point of view. In Fig. 11(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, Fig. 11(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.

More specifically, the GWP for most coal gasification ranges from 2.0×10^8 kg CO_2 eq. to 1.3×10^8 kg CO_2 eq. However, some results show that it can rise up to 2.8×10^8 kg CO_2 eq. On the other hand, it can be seen that the distribution range of GWP results for other options is significantly smaller than that of coal gasification. On the other hand, in AP, the result distribution range of diesel propulsion ranges from about 0.5×10^6 kg SO_2 eq. to 2.0×10^6 kg SO_2 eq. However, some results show the potential to rise significantly higher, up to 4.3×10^6 kg SO_2 eq. The distribution of these results appears in the same pattern in EP. LNG, coal gasification, and diesel propulsion have a very wide distribution of environmental impact impacts, and the maximum impact is found to be very strong compared to hydrogen fuels other than hydrogen produced by coal gasification. In conclusion, the results from a statistical point of view also show similar patterns to the previous analyses.

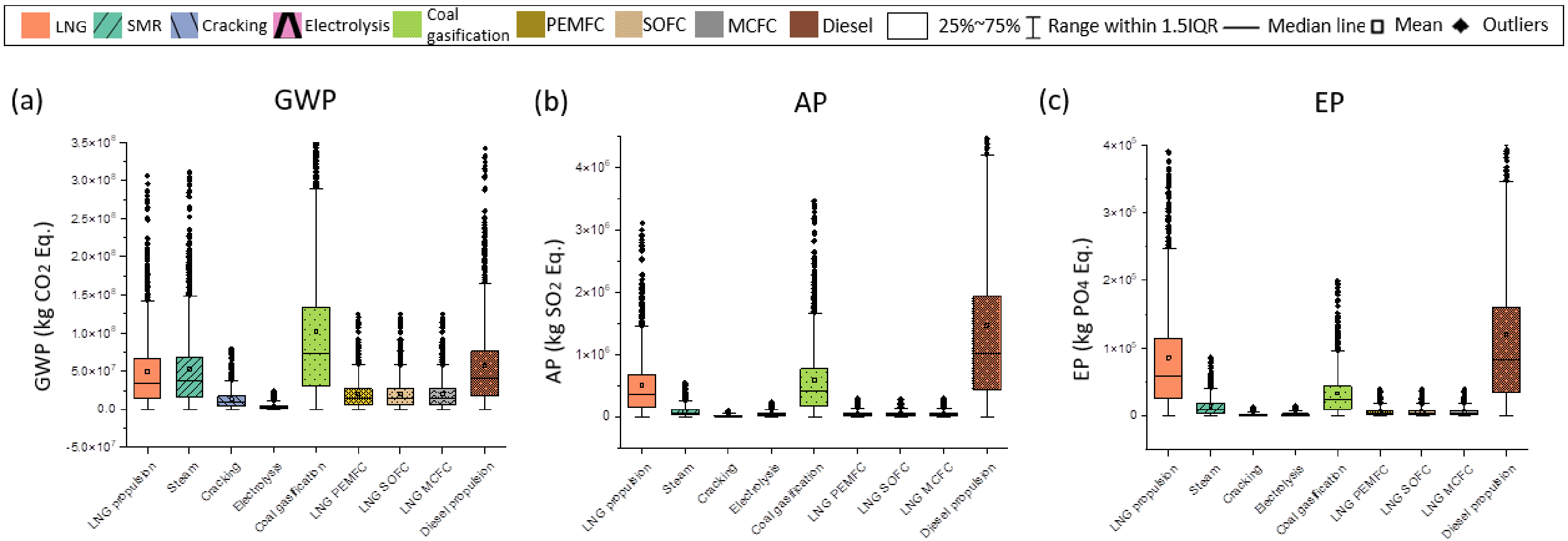

Fig. 11. Box plot chart results according to fuel & propulsion types.

4. Discussion

Hydrogen fuel cells are now recognized as one of the most promising future alternatives to resolve IMO compliance and marine environmental challenges in the shipping sector. Along with various and diverse studies on pursuing the demonstration of technical maturity of fuel cells and the environmental benefits, a differentiated LCA study to obtain general observations on the life cycle impact of hydrogen fuel cells can be found as novelty of this paper.

The conventional LCA was designed to focus only on specific case studies, so it was difficult to apply it to general and broad fields such as environmental regulation, policy, and future investment. On the other hand, PT-LCA was developed to utilize the concept of the conventional LCA to perform thousands of cases simultaneously while correlating inputs and outputs to obtain a consistent trend. After all, a series of simple equations called environmental indicators are proposed as given in Appendix.

The proposed indicators are fully accessible to anyone who are interested in calculating the holistic environmental impacts of any type of hydrogen fuelled ships without any piece of knowledge on LCA. As a result, they can make a great contribution to determining the optimal energy solutions for the entire vessels around the world.

Meanwhile, LCA research in this paper has been conducted with limited information and data at hand as referring to the data from the past LCA studies. Thus, the proposed indicators should be subject to the continual review and update, by enhancing the quality of data.

Also, 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. To improve the reliability, the proposed indicators may be necessary to be upgraded with polynomial equations that can consider the impacts of various inputs on the outputs at the same time.

Nevertheless, the proposed indicators offer a great deal of the comprehensive information that cannot be obtained with the traditional approaches that normally offer some limited information as a form of functional units as final outcomes. This is because functional units obtained from conventional LCAs may be useful for the target vessel of the study, but do not provide much information about other vessels.

As a result of the research, it was revealed that hydrogen fuel can contribute to reducing life cycle emissions from shipping activities. Thus, there are two options to answer the fundamental question that hydrogen fuel cells can be a greener alternative: to produce grey hydrogen with minimal emissions, or to build a green hydrogen infrastructure as quickly and cheaply as possible.

Among these two answers, since more than 90% of the world hydrogen production is grey hydrogen produced from fossil fuels, it is expected that producing grey hydrogen with minimal emissions would be closer to a more fundamental answer. This is not the perfect answer to achieve cleaner shipping. However, research shows that this case may be cleaner than LNG and diesel propulsion systems, so it could be an alternative for these fuels for the time being.

Therefore, while studying how to minimize emission when producing grey hydrogen, if green hydrogen infrastructure is established faster and cheaper, we can further facilitate green shipping ahead.

5. Conclusions

Conclusions can be summarized as follows:

1) 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. To be specific, among the hydrogen production methods, cracking and electrolysis hydrogen production methods are the greenest, while coal gasification and steam methane reforming hydrogen are the worst green methodologies. Nevertheless, hydrogen fuel cells can be bridge alternatives of LNG and diesel with even grey hydrogen as long as it is produced under the well-controlled conditions.

2) When using LNG directly as fuel for fuel cells, well-to-tank phase is about 100 times greater than tank-to-wake phase. Therefore, although it is revealed that SOFC is the greenest fuel cell, when the entire life cycle is considered, the difference in environmental impacts between fuel cells is drastically reduced because the well-to-tank emissions from LNG is significant.

3) Compared to conventional fossil fuels, the propulsion method through the LNG fuel cell is more eco-friendly than the LNG propulsion ship. Therefore, when LNG is used as fuel, it is more eco-friendly to operate with fuel cells than with conventional internal combustion engines.

4) Research findings may contribute to the development of environmental regulations for a future hydrogen society. Specifically, by demonstrating that ship power provided in the Annex is closely related to environmental impact, a simple formula can contribute to the selection of general criteria for setting future energy policies and regulations. By making environmental

impact assessments easy, simple, and fast, we deliver meaningful results for a wide range of stakeholders.

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Appendix

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

	Equation	Residual Sum of Squares	Pearson's r	R-Square (COD)	Adj. R-Square
(a) 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
(b) LNG WTT $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 39.4 \times \mathcal{X} - 7.2$E3	1.45E12	0.78464	0.61566	0.61546
(c) 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
(d) 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
(e) 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
(f) 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
(g) 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
(h) LNG WTW $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 452.6 \times \mathcal{X} - 8.3E4$	1.91E14	0.78464	0.61566	0.61546

(i) 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
(j) 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
(k) 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
(l) 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 A 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 $\mathcal{Y} = GWP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 19172.2 \times \mathcal{X} - 3.5E6$	3.44E17	0.78428	0.6151	0.6149
(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 A 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	$\mathcal{Y} = 12.9 \times \mathcal{X} - 2.0E3$	1.64E11	0.777	0.60373	0.60352

$\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$					
(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 $\mathcal{Y} = EP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 29.7 \times \mathcal{X} - 4.8E3$	8.67E11	0.777	0.60373	0.60352

Table A 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 $\mathcal{Y} = AP$ $\mathcal{X} = Vessel\ power$	$\mathcal{Y} = 18.3 \times \mathcal{X} - 2.9E3$	3.32E11	0.777	0.60373	0.60352
(i) Electrolysis WTT $\mathcal{Y} = EP$	$\mathcal{Y} = 1.0 \times \mathcal{X} - 1.7E2$	1.12E9	0.777	0.60373	0.60352

$\mathcal{X} = Vessel\ power$					
(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