



Application of parametric trend life cycle assessment for investigating the carbon footprint of ammonia as marine fuel

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Abstract

Purpose This study aimed to determine whether ammonia can genuinely help to reduce the carbon footprint of maritime activities. Given this, it was decided to investigate the life cycle of ammonia and its impact on the environment regarding the global warming potential.

Methods To achieve this goal, the parametric trend life cycle assessment was applied to yield a general and reliable observation. The research was combined with a comprehensive dataset of over 2061 bulk carriers and eight different ammonia production methods: steam methane reforming, photovoltaics, electrolysis via wind, biomass downdraft gasifier, biomass circulating fluidized bed gasifier (CFBG) system, underground coal gasification (UCG) with carbon capture and storage (CCS), UCG without CCS, and 3-step Cu-Cl cycle. In addition, an existing ME-LGI (ME-liquid gas injection) engine was selected as the propulsion system.

Results The results from PT-LCA revealed that for estimating the carbon impact of ammonia as marine fuel from a well-to-wake (WTW) perspective, it is mandatory to focus on the well-to-tank (WTT) phase. The lowest carbon production pathway for the global warming potential (GWP) is the 3-step Cu-Cl cycle and eventually is the most potential route for using ammonia as fuel in the maritime industry. Finally, this study concludes with some formulas, based on regression analysis, which serves as rapid indications for comparing the overall carbon impact of thousands of bulk carriers equipped with the ME-LGI engine, carrying ammonia as fuel from different production methods.

Conclusions Given these fuel production routes, the research has also demonstrated that ME-LGI engines can be a groundbreaking way to reduce the carbon footprint of ships. Additionally, the research findings showed that the environmental indicators proposed in this article have the potential to make a significant contribution to the industry. They are anticipated to assist stakeholders in overcoming the discrepancy problem generated by past studies that were so dissimilar from case to case that the scope, boundary of analysis, data, and assumptions they employed were far from current standards and rules. In addition, the GWP according to the ship power was compared and reviewed in terms of the well-to-wake (WTW). Thus, the proposed methodology for developing ammonia ship environmental indicators is to provide valuable insight into environmental policy and decision-making processes.

Keywords PT-LCA · Ammonia · Marine fuels · Life cycle assessment · Decarbonizing shipping

Abbreviations

ABS American Bureau of Shipping
AP Acidification potential
BSFC Brake-specific fuel consumption

CCS Carbon capture and storage
CEAS Computerized engine application system
CFBG Circulating fluidized bed gasifier system
COD Coefficient of determination
DNV Det Norske Veritas
EGR Exhaust gas recirculation
EP Eutrophication potential
GHG Greenhouse gases
GWP Global warming potential
HFO Heavy fuel oil
IACS International Association of Classification Societies

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IGF Code	International code of safety for ships using gases or other low-flashpoint fuels
IMO	International Maritime Organization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LNG	Liquefied natural gas
LHV	Lower heating value
ME-LGI	ME-liquid gas injection
MEPC	Marine Environment Protection Committee
MGO	Marine gas oil
PM	Particulate matter
PT-LCA	Parametric trend life cycle assessment
PV	Photovoltaics
SCR	Selective catalytic reduction
SFOC	Specific fuel oil consumption
SO _x	Sulfur oxides
TE-LCA	Technology evolution LCA
TTW	Tank-to-wake
UCG	Underground coal gasification
UN	United Nations
VLSFO	Very low sulfur fuel oil
WTT	Well-to-tank
WTW	Well-to-wake

1 Introduction

1.1 Overview

With the growing concern about the climate crisis, the International Maritime Organization (IMO) has agreed to reduce greenhouse gas (GHG) emissions from the marine industry by 40% and 50% by 2050 compared to 2008 (Hansson et al. 2020). To achieve this ambitious goal, the IMO resolution marine environment protection committee (MEPC.304(72)) adopted the initial IMO strategy for the reduction of GHG emissions from ships in April 2018 (ABS 2020).

Currently, the main fuel for the shipping industry is diesel fuel, which must be converted to zero-carbon fuels such as ammonia to comply with the IMO regulatory framework (DNV-GL, 2020). It is because its combustion reduces significant amounts of GHG and other pollutants when compared to diesel fuels (ABS 2019).

1.2 Literature review

Ammonia can be made from natural gas produced through water electrolysis or from fossil fuels (ABS 2021). While ammonia produced from fossil fuels has a large carbon footprint as it requires extremely high energy and cannot achieve the goal of utilizing zero-carbon fuels, the production of ammonia from water using renewable energy

on a life cycle basis has the potential to eliminate carbon emissions to ammonia (ABS 2021).

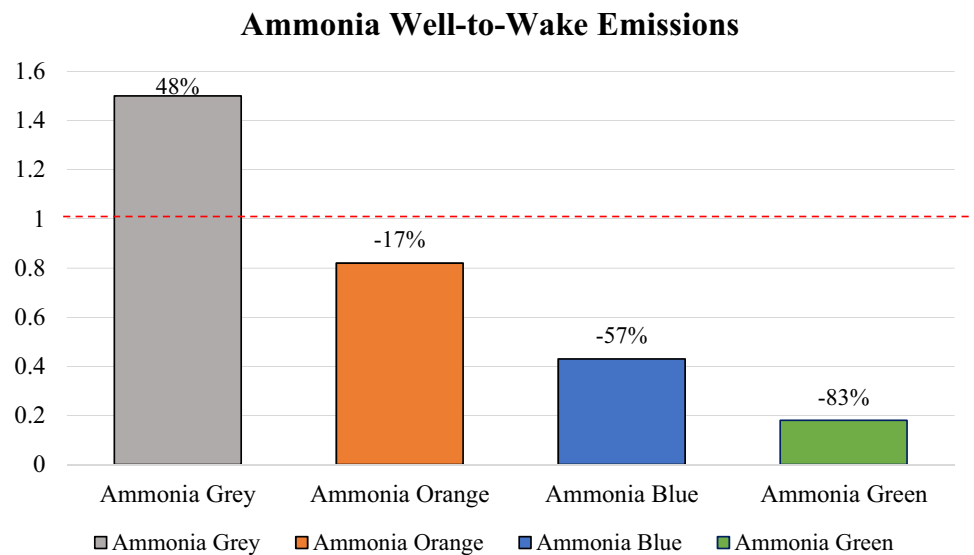
As such, depending on the ammonia production method, it is uncertain whether or not ammonia can be an eco-friendly fuel for ships. Thus, a novel environmental evaluation has been required in the shipping industry on whether ammonia is suitable as a fuel for ships. Nowadays, the LCA is becoming a trend in the maritime sector. Some quite interesting studies are published, and one of them comes from Bengtsson et al. (2011), who are keen on investigating the impact of each alternative fuel in the maritime sector. Another compelling study comes from Blanco-Davis and Zhou (2014), who outlines a basic refit conducted on a case study vessel to do a life cycle evaluation to determine the retrofit's possible environmental consequences. Also, González-García et al. (2013) have examined biofuel production from a life cycle perspective regarding the transesterification of crude rapeseed oil which is one of the most important sources of biodiesel in Europe. One more alternative fuel, LNG, is the subject of several absorbing studies by Tagliaferri et al. (2017). They select the LCA method to investigate the different possible options of how LNG can be imported to the UK.

Focusing on ammonia, ABS (2021) has found some interesting results as observed in Fig. 1. They compare well-to-wake (WTW) emissions of very low sulfur fuel oil (VLSFO), with green, blue, gray, and orange ammonia. Green ammonia is produced from the electricity that comes from renewable sources. Gray ammonia is a product of natural gas. Blue ammonia has the same source, while a carbon capture system is responsible for seizing the carbon emissions from the conversion process. Orange ammonia is a mixture of half gray and green. It is found that the green version has 83% lower life cycle carbon emissions, blue ammonia has 57% lower, orange has 17% lower, and gray has 48% greater life cycle carbon emissions than VLSFO. At the same time, DNV-GL (2020) expanded its research to the financial and operating field and examines if ammonia could be vital also in other fields of the industry. Moreover, De Vries (2019) explored several case vessels and potential engines to investigate how ammonia application can be more effective and safe at the same time. In addition, there is also a great focus on safety issues of ammonia handling and storage, which needs further investigation and a quite extensive risk assessment.

Related to ammonia production, Bicer et al. (2016) compare four alternative ammonia manufacturing technologies. The findings of a LCA for ammonia production processes show that municipal waste incineration plants and hydropower-based techniques are the most environmentally friendly.

Another extended related LCA study conducted by Zamfirescu and Dincer (2008) focused on the sustainability

Fig. 1 Comparison of different types of ammonia in well-to-wake CO₂ emissions against VLSFO (ABS 2021)



of ammonia. It is compared with other fuels like hydrogen, not only from a financial point of view but also from the perspective of supply chain needs. Similarly, Linstad (2020) found that both hydrogen and ammonia consume about twice as much energy on a WTW basis as conventional fuels. Thus, even if generated from green electricity, the cost would be higher assuming the used energy. Trying to examine further the potentiality of ammonia as a profitable choice for the global economy, MacFarlane et al. (2020) were focusing on a multiscale study that aims to prove that it is a feasible fuel to invest in.

1.3 Research gap and limitations

One of the limitations of most ammonia LCA studies in the shipping industry has focused only on the ammonia production phase. It is because the reliability of the ammonia LCA results is under consideration due to the lack of information regarding the use of ammonia in the maritime sector. Therefore, for genuine ammonia LCA study, an analysis of ammonia consumption is also required to evaluate whether ammonia can reduce a ship's carbon footprint from a life cycle perspective.

The lack of TTW emissions data reveals another vital question, as there is an absence of marine engines which can burn ammonia and be suitable for the majority of vessels. Ammonia was utilized in buses in Belgium in 1942 during World War II (Brohi 2014). Later, in the 1960s, Starkman conducted both theoretical and practical investigations to see if ammonia might be used as a fuel substitute for internal combustion and spark-ignition engines (Starkman et al. 1967). Following the above, it can be stated that ammonia fuel research has been extremely restricted until recently.

Most of the research, nowadays, is focused on the combustion of ammonia and the selection of the most suitable pilot fuel. Specifically, Oh et al. (2021) studied experimentally the case of natural gas–ammonia, dual-fuel spark-ignited engine with emphasis on its suitability for maritime applications. To run dual-fuel combustion with different air–fuel ratios and ammonia split ratios, an 11-L 6-cylinder turbocharged spark-ignited engine is employed. The air–fuel ratio is found to be limited to a lambda value of 1.5, causing combustion efficiency and emission characteristics to deteriorate. Before that, Durgun et al. (2018) examined experimentally, in a small diesel engine, the effects of ammonia fumigation on performance and exhaust emissions. Particularly, by using 25% of ammonia and 75% of water, they found that brake-specific fuel consumption (BSFC) increases between 2000 and 3000 RPM, but reduces at 2600 RPM, according to the test findings. At 2600 RPM, the greatest decrease of BSFC was found to be 7.28 % for a 5.48 % ammonia ratio.

Moreover, Kim et al. (2020) have compared commercial main engines of the maritime sector, with four different potential propulsion systems that could combust ammonia in a 2.500 TEU container ship. They found that the most ecological solution is the SOFC technology but at the same time the most expensive. Another study has conducted by Zacharakis-Jutz (2013), who investigates the performance of several direct injection techniques of ammonia fuel in several cases and analyzed the data for observing the nature of the fuel during the combustion.

Following that, manufacturers like MAN understood the need for the establishment of a new era in marine engines. By building the first 2-stroke ammonia engine by 2024, MAN realizes how carbon-efficient ammonia could be for the industry (MAN 2020). This is the reason why they have to invest in a new engine model, which will probably follow

the principles of the ME-LGI. This dual-fuel engine, in particular, allows ammonia to join the marine industry as a critical option for any vessel which is obligated to meet the IMO decarbonization standards by 2050. Research from ABS insists that small technical changes to the fuel delivery system might convert ME-LGI to an ammonia-fueled engine (ABS 2020).

Indeed, nowadays, big manufacturers have already started testing novel engines, but it is also true that until 2025 the state-of-the-art technologies related to ammonia combustion will not be published on the market.

Moreover, the conventional LCA methodology has focused on a case-by-case analysis. This could cause the problem that the LCA results of the studied vessel cannot be applied to other vessels. In the shipping industry, there are various stakeholders such as ship owners, shipbuilders, operators, and lawmakers. Since each stakeholder owns and handles different vessels, it should be possible to satisfy all stakeholders with the overall LCA results from whole fleets, not the LCA result of a few case ships.

According to ISO 14040 and ISO 14041, the LCA can be applied only for case-specific studies. This fact proves that is an inadequate methodology for building new regulatory frameworks and decision-making procedures. Specifically, the specific orientation of boundaries during the phase of goal and scope does not allow the methodology to be a pioneer tool to establish new trends and pathways (Guinée 2002; ISO 2006).

Focusing on the maritime industry, the LCA is vital but it also has limitations. Firstly, due to the case-specific nature of this methodology, it is not efficient from the scope of time and economy. Secondly, this methodology is conducted under case-specific boundaries and limitations, a fact that cannot reveal reliable results when the decision-makers need to proceed with activities related to a whole fleet and probably with different types of vessels. After these limitations, the establishment of an appropriately applied methodology for a different application that can fill these gaps is inevitable.

To overcome these limitations, Jang et al. (2020) developed a parametric trend life cycle assessment (PT-LCA) and applied it to 1565 ocean-going Ro-Ro vessels, not a few case ships. As a result, by revealing the correlation with environmental impacts according to age and power, which are basic information about ships, various stakeholders can easily and quickly obtain consistent environmental impact results from a life cycle perspective.

PT-LCA was based on ISO criteria, but instead of a single data point for one or two case ships, it employs thousands of data points throughout the whole fleet. Furthermore, the incorporation of the parametric trend analysis procedure distinguishes it from traditional LCA in that the ultimate objective is to represent worldwide policy through general

observation by inferring the trend of the whole fleet's LCA findings, rather than just one unique LCA result. Consequently, whereas the traditional LCA only calculates the individual LCA result of a single vessel, the PT-LCA calculates the overall LCA results of thousands of boats (Jang et al. 2020).

This methodology has also been applied to LNG-fueled vessels. As a result, the numerous equations revealed from regression analysis enable numerous stakeholders to predict life cycle emission predictions for different types of dual-fuel engines on different ships (Jang et al. 2021).

The lessons learned from previous research in the field of alternative energy sources have proven that there is plenty of room to approach a problem by using a state-of-the-art methodology like PT-LCA, especially, when there is a great need for a tool that will contribute to the development of new regulations and frameworks for ammonia. This novel methodology is LCA-based and utilizes past LCA studies to contribute to numerous stakeholders who are not familiar with environmental assessment and regulatory frameworks. This fact would be helpful for the development of new regulations for ammonia because the results of PT-LCA could represent the carbon footprint of a fleet of vessels that utilize this fuel. Therefore, stakeholders who will use this tool can save time and cost during the carbon evaluation of their fleet, and also ammonia will increase the possibility to be established as a carbon-friendly source of energy for the maritime industry.

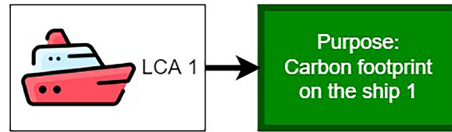
1.4 Contribution of this research

LCA research has mostly been done on a case-by-case basis, with a single or two case ships being chosen for various design and operational situations. However, as demonstrated by literature reviews, these study findings have inherent limitations, such as the fact that LCA results produced from case studies may not apply to other case ships with various ship characteristics and operating itineraries.

On one hand, LCA conclusions from a single case study cannot be used to develop marine environmental policy or serve as general recommendations for thousands of ships. On the other hand, the PT-LCA was designed to provide valuable insight into maritime policymaking and regulatory frameworks involving thousands of ships. PT-LCA was created using ISO criteria; nevertheless, instead of a single case ship, it incorporates data from the whole fleet (thousands of ships). The comprehensive ship data is utilized in the parametric trend analysis process, which is a major feature of PT-LCA, in which the LCA procedure is repeated thousands of times and the LCA findings for each ship. Figure 2 shows the difference between conventional LCA and PT-LCA.

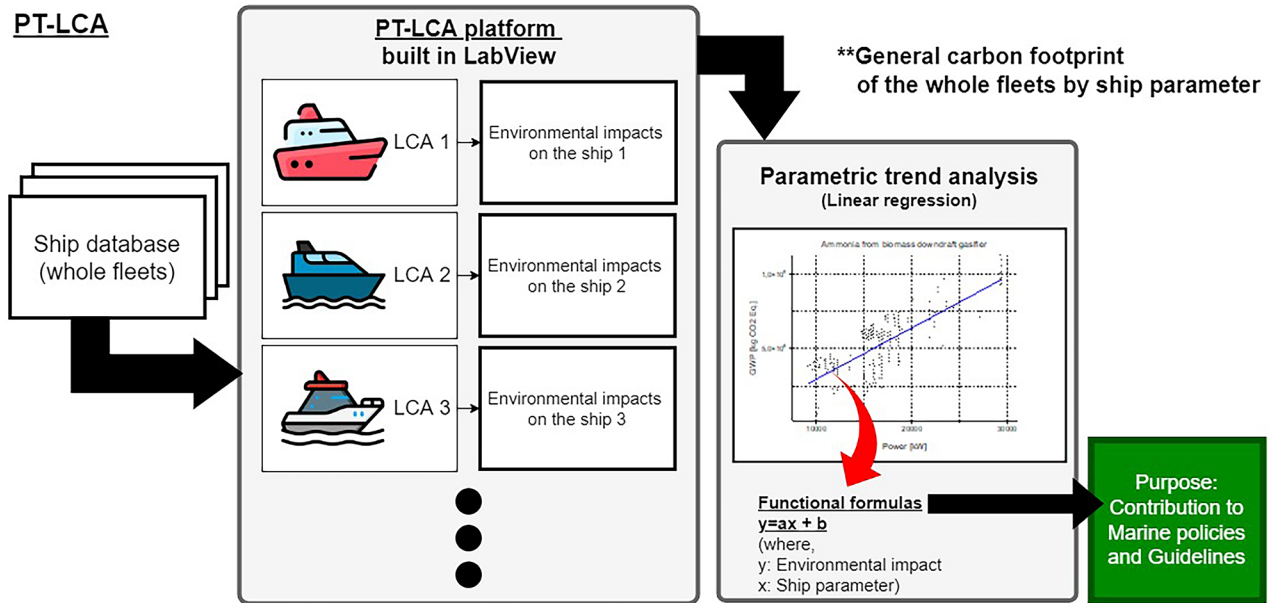
After that, the data were summarized and condensed into global warming potential (GWP) indicators. Then it is

Conventional LCA



****Specific carbon footprint of the only single case ship (Not applicable for other ships)**

PT-LCA



****General carbon footprint of the whole fleets by ship parameter**

Fig. 2 Brief comparison between conventional LCA and PT-LCA

allowed to comprehend and assess the quantifiable relationships between the carbon impact of ammonia as marine fuel and ship features during their entire existence. For example, the input value was set to the ship’s power and the output value was set to GWP. Eventually, it could be seen how much ship power affects the production of carbon emissions in the maritime sector. These carbon indicators may be used to understand the behavior of whole fleets of bulk carriers. They can subsequently be utilized to inform international policy by general observation and inferring the trend of the entire fleet’s LCA findings.

Meanwhile, climate change is one of the most urgent issues across the world. Indeed, like other industries, the marine industry is strongly urged to achieve carbon-zero shipping within this century. As a result, GWP from shipping activities is a standard to determine clean shipping or not.

Following the current issues, this research aims to utilize PT-LCA to find the carbon impact of a fleet using ammonia as fuel. Furthermore, a model of the ammonia-fueled engine should be created, based on the literature review and the current data from manufacturers. After that, a better estimation of the TTW part of this research will be conducted by estimating the potential SFOC. In this context, this paper has been motivated to contribute to curbing climate change in the shipping sector to meet the global shipping target of a

50% reduction in GHG emissions by 2050. Given this, PT-LCA in this paper will be focused on GWP impact alone.

For the implementation of this research, a huge database that covers the whole fleet rather than just a few case ships as well as a diverse set of prior LCA findings with broad scopes and research backgrounds regarding ammonia will be taken into consideration. Following the collection of these databases, a modified LCA calculator capable of doing thousands of LCAs at once was built. With this improved application, a wide range of carbon effect outcomes could be contained within simple formulae, specifically indicators, which could be used to quickly assess a ship’s carbon potential performance in a larger context.

The findings of the analysis are compiled into basic equations that will be used to create GWP indicators. The suggested standards will undoubtedly be beneficial for assessing ammonia’s overall carbon performance for global shipping. Additionally, they will be easily accessible to members of the public who are unfamiliar with LCA but are curious about the benefits and drawbacks of utilizing ammonia as a marine fuel. A more accurate comparison of ammonia with other alternative fuels could be conducted and reveal which is the most carbon-friendly choice for the industry.

By offering practical insights and recommendations to help stakeholders and policymakers better understand how

ammonia can enter as a fuel in the maritime sector, the research aims to contribute to guiding future policies and regulatory frameworks in the correct direction.

The next sections will follow a step-by-step process, in which all the methodologies are described.

2 Methodology

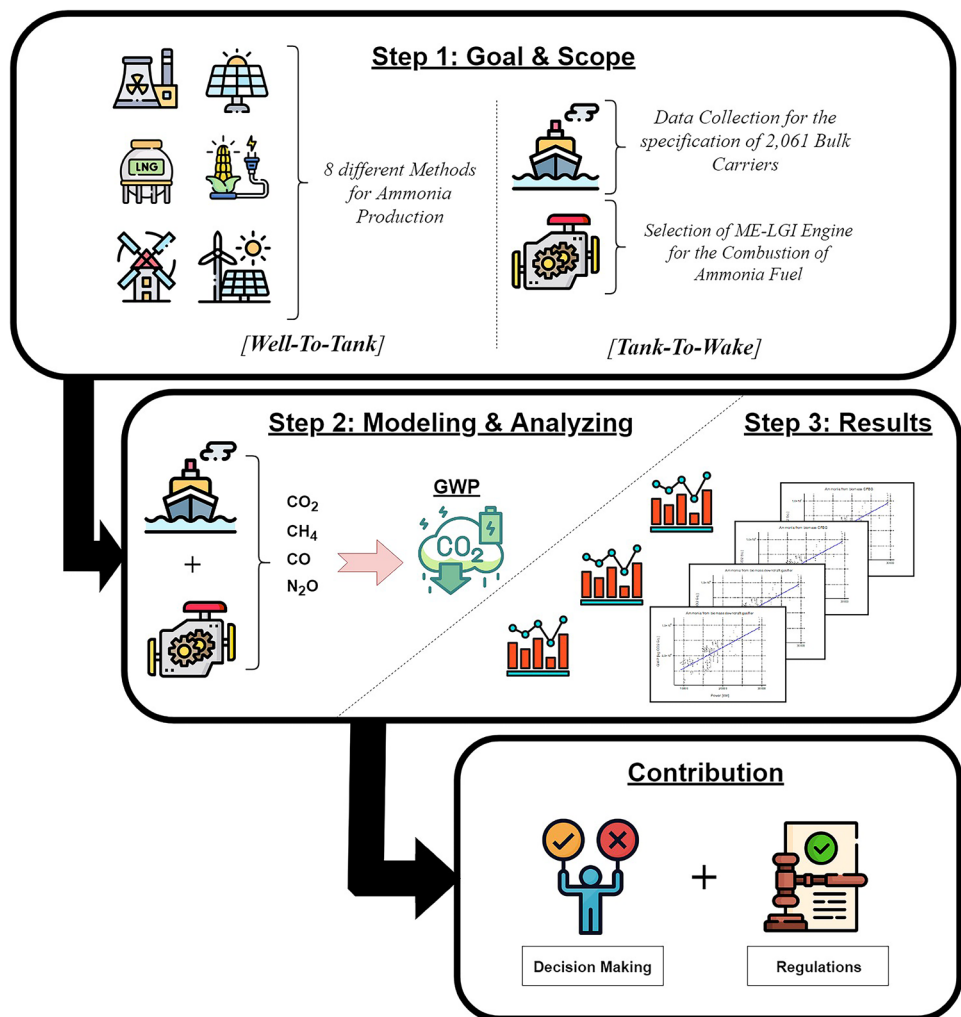
As already mentioned, initially, the PT-LCA method was used to investigate the various environmental impacts of the scrubber systems. This study concluded that scrubber systems contribute significantly to reducing acidification potential (AP), whereas GWP and eutrophication potential (EP) do not. Also, it found that the age and power of the ship had a strong correlation with environmental impacts (Jang et al. 2020).

Since then, PT-LCA has been applied to LNG-fueled ships revealing a meaningful conclusion that the eco-friendliness of LNG can be changed depending on the LNG production

pathways (Jang et al. 2021). Therefore, PT-LCA is a method that has been developed and applied to ship fuels and systems to draw broader and more insightful conclusions by analyzing environmental impacts not only for one case ship but also for the entire fleet.

Figure 3 shows the flow diagram of applying PT-LCA to analyze the GHG results that occur when eight pathways producing ammonia are applied to over 2000 ships. The entire process for using ammonia in ships consists of two life stages: well-to-tank (WTT), which is a stage from ammonia production to transport to the ship, and tank-to-wake (TTW), which is the fuel consumption phase in ships. As shown in Fig. 3, PT-LCA consists of three main phases: goal and scope, modeling, and results. In the first two phases which are the goal and scope and modeling phases, ISO guidelines were followed applying to the PT-LCA platform. Therefore, after setting the goal and scope of the research, identifying and quantifying GHG emissions such as CO₂ and CH₄ are completed for thousands of ships. Based on the results, the step of estimating GWP is followed (Fig. 4).

Fig. 3 Flow diagram of PT-LCA method for ammonia



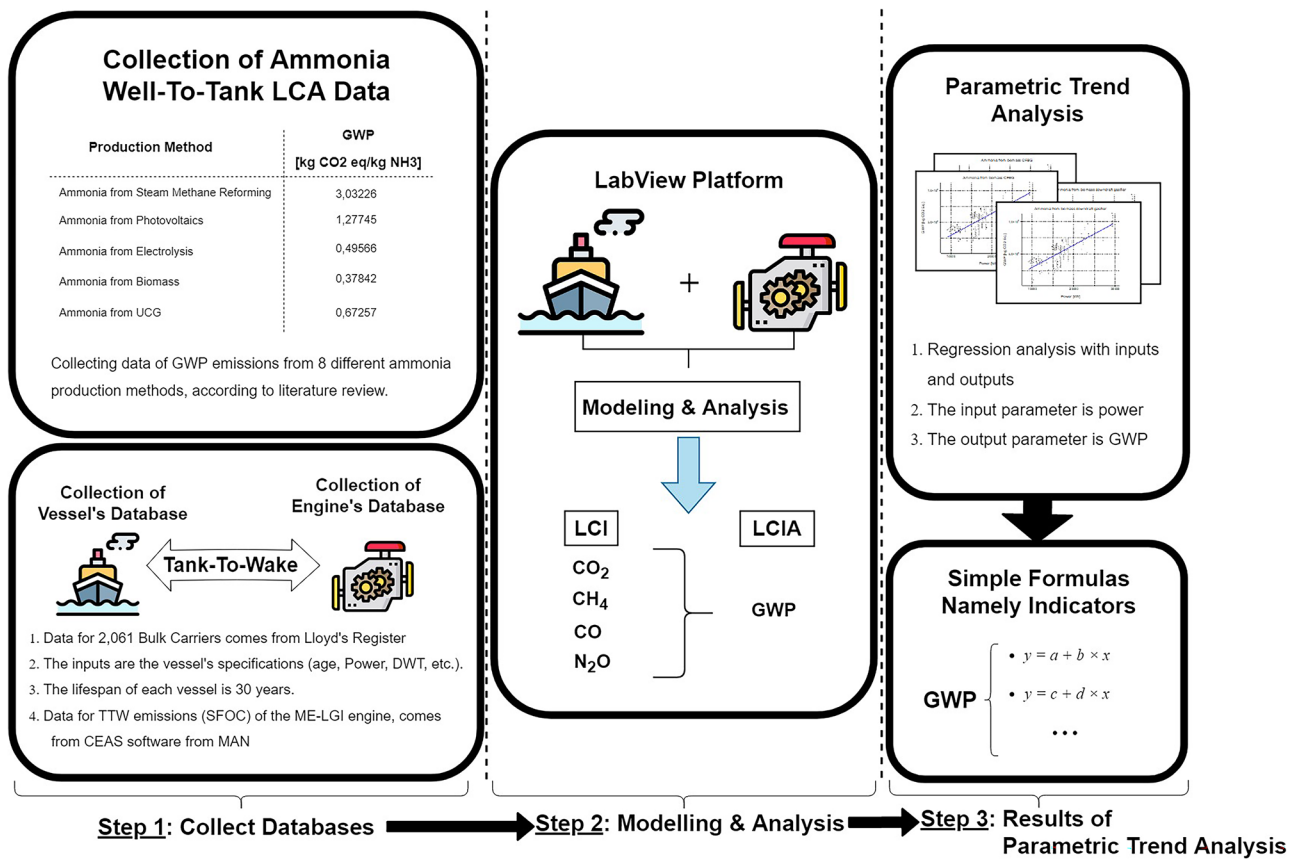


Fig. 4 Flow chart of PT-LCA method for ammonia

The difference from the conventional LCA is that it only calculates the individual result of a single vessel while the PT-LCA calculates the general LCA results of thousands of ships. A calculation platform must be configured for this and a huge dataset must be collected to perform PT-LCA.

In the third and final stages, a single trend line according to the ship power, which is one of the ship parameters, will be plotted. Linear regression of the GHG result values generated from the thousands of ship databases will be used and derived by several simple equations. Therefore, the specific correlation between the ship's basic information such as age and power as input parameters, and the output parameter which is environmental impacts, can be identified.

2.1 Phase 1: aim and scope

2.1.1 Scope of research

From well-to-wake (from energy production to onboard usage), this study delves deeply into the environmental consequences of GWP by utilizing ammonia as a maritime fuel. There are two stages to the life cycle of ammonia:

- Well-to-tank (WTT)
- Tank-to-wake (TTW)

The WTT, also known as upstream, depicts the life phases that occur between the extraction of raw materials, ammonia processing, and the supply chain, all the way to ultimate arrival onboard. After that, the onboard usage phase is embodied by the TTW, or downstream.

The LCA results from earlier research related to the different production methods of ammonia are summarized in Table 1. The PT-LCA uses the maximum and lowest routes as input parameters for WTT analysis, allowing it to quantify the carbon effect of a fleet of vessels and see how the findings change depending on the input sources.

The TTW study combines a marine database that includes full ship specifications for one of the most frequent types of ships involved in merchant services worldwide, the bulk carriers. At that part is vital to be mentioned, that due to the lack of engines that can burn ammonia as fuel, the novel ME-LGI engine from MAN is used for estimating the TTW emissions. This specific engine is integrated with the whole fleet of bulk carriers, allowing for the estimation of

Table 1 Input data for well-to-tank emissions from different production methods

Production method	GWP (kg CO ₂ Eq./kg NH ₃)	Source
Ammonia from steam methane reforming	3.03226	Singh et al. (2018)
Ammonia from photovoltaics	1.27745	
Ammonia from electrolysis via wind	0.49566	
Ammonia from biomass downdraft gasifier	0.37842	
Ammonia from biomass CFBG	0.37842	
Ammonia from UCG with CCS	0.67257	
Ammonia from UCG without CCS	3.85401	
Ammonia from 3-step Cu-Cl cycle	0.33230	Karaca (2019)

environmental correlations between ships and the ME-LGI engine.

The main scope and the principal boundaries of this research are presented below:

- The GWP emissions, such as CO, CO₂, CH₄, and N₂O, are examined primarily using data from the literature.
- Lloyd's Register has created a database of thousands of bulk carriers.
- Without berthing or anchoring, the vessel's life expectancy is estimated to be 30 years.
- ME-LGI is selected as the most potent type of ammonia-fueled engine.
- Regarding the LCA models, the WTT phase is based on several methodologies of ammonia production (Singh et al. 2018) and TTW from the assumption of onboard consumption originating from MAN CEAS engine calculations software.
- The PT-LCA functional units are mathematical equations that indicate connections between ship fundamental data and environmental effects, based on regression analysis.

2.1.2 Data collection

Bulk carrier As mentioned earlier, bulk carriers are selected to be the subject of this research, as it is the most common merchant vessel worldwide. As a result, the required data for the complete fleet of 2061 bulk carriers were gathered using the Lloyd's Register maritime database, which contains hundreds of ship parameters such as flag, age, power, and DWT. The ships in the database are categorized according to their age, which ranges from 0 to 30 years. Furthermore, the engines on such vessels range in capacity from 9.120 to 29.400 kW, and the range of deadweight from 87.665 to 403.880 tons.

ME-LGI ammonia engine The ME-LGI engine was not chosen at random. There is indeed no commercial main engine that runs on ammonia as a fuel today. But it is for this novel reason that ME-LGI was chosen. This dual-fuel engine allows ammonia to join the marine industry as a critical

option for any vessel that must meet the IMO decarbonization standards by 2050.

The ME-LGI engines are dual-fuel engines that run on diesel and methanol or LPG, according to the manufacturers. However, MAN stated that this technology is more appropriate for ammonia rather than methanol. Small technical changes to the fuel delivery system, such as delivering ammonia at 70 bar and injecting it into the cylinder at 600–700 bar, might convert the ME-LGI to an ammonia-fueled engine (ABS 2020). One of the most significant obstacles is that ammonia is a low-flashpoint fuel. Slow flame velocity, ignition temperature, flammability range narrowing, and decreased heat of combustion are all problems with ammonia ignition. That is why it requires two times the volume of a VLSFO to produce the same amount of energy.

The usage of ammonia as a marine fuel is not as benign as it may appear from an environmental standpoint. During combustion, there is a risk of ammonia leakage if the exhaust valve fails. As a result, unburned ammonia may be discharged, posing serious risks not only to the materials with which it comes into contact but also to humans and the environment due to its poisonous nature. However, the ME-LGI system, which uses a high-pressure direct injection system to feed ammonia fuel later in the compression stroke, provides a solution to this problem. As a result, the ammonia leak will be less of a concern. Aside from ammonia slip, the generation of NO_x during combustion must also be considered. According to recent studies, ammonia may create almost as much NO_x as VLSFO while also removing CO₂. As a result, NO_x control is critical, and the use of the SCR system is required, and it is regarded as a critical solution.

2.2 Phase 2: modeling

The traditional LCA method focuses on obtaining unit functions, which are typically structured as emission amount per unit of energy use (i.e., kg/kWh). The PT-LCA, on the flip side, provides the input-output correlations. Basic vessel statistics from Lloyd's Register, such as power, age, and tonnages, will be used as inputs in this research, while

environmental consequences of GWP will be used as outputs. Therefore, anybody with access to the correlations may quickly determine a ship's carbon potential impact. The approach to building appropriate LCA models to achieve such correlations is covered in Section 2.2, of this study.

The LCI model can be thought of as a platform for analyzing inputs and calculating emission amounts. This model combines input characteristics with life cycle emission factors derived from previous LCA research. As a result, it quantifies the carbon emissions into two stages:

- Well-to-tank (WTT) emissions
- Tank-to-wake (TTW) emissions

Different production methodologies are about to be analyzed in the next chapters regarding the WTT carbon emissions. The results from CEAS software are about to be used as an efficient approach for estimating the TTW carbon emissions.

2.2.1 Well-to-tank (WTT) emissions

Most of the past research related to ammonia is focusing on the production phase of the potential fuel. Specifically, the prestigious Haber-Bosch is the main technology that is commonly used nowadays and several researchers are inspired to conduct some quite interesting LCA studies with a variety of boundaries and scopes.

Regarding the WTT emissions, Singh has made a comparative study and published results related to the environmental impact of different production methods (Singh et al. 2018). Another research has been made by Karaca, who conducted a life cycle assessment of nuclear-based hydrogen and ammonia generation (Karaca 2019). The sources above have been used as the main source of data for the WTT phase of this study. Both publications have used the generally accepted ecoinvent database, as they utilize the SimaPro software for their analysis. Also, for the LCI analysis, CML 2001 and Eco-indicator 99 are used. However, no sensitivity or uncertainty analysis is traced, something that could be a limitation.

Consequently, Table 1 is created according to the mentioned literature above, to illustrate the main inputs for estimating the WTT phase of the PT-LCA for this study. Further details regarding each procedure can be found in the Appendix section.

2.2.2 Tank-to-wake (TTW) emissions

The TTW research could achieve consistent conclusions by assuming that each ship would be always operated at the design speed of 100% engine power, to analyze the environmental impact of the case scenarios. Particularly, the results

of CEAS software, Table 2, are vital in this stage to estimate the suitable information for the fuel consumption to proceed to further calculations and results. Individuals may create a new project with various calculations and design options in the simplest way possible through the manufacturer MAN CEAS engine calculations software. Everyone has access to a variety of options for selecting MAN engines (models) and auxiliary systems in that software (EGR, SCR, number of turbochargers, etc.). By using this software, the fuel consumption of the potential ammonia engine was estimated and used in the TTW phase of the LCA models of this research. These data, Table 2, are about to be used as inputs for the TTW phase of the PT-LCA methodology.

With the previously stated assumption of a vessel's lifetime, without berthing and anchoring, being 30 years, the total fuel consumption of each vessel may be calculated using specific fuel consumptions (SFOC and SGC) and engine efficiency. The inputs that are used for calculating the TTW emissions of this study are summarized in Table 4.

Due to the assumption that all the bulk carriers that are used for this study are equipped with the same ME-LGI engine, it is easily observed that the TTW phase is similar for all the cases and eventually there will be no actual differences between them. However, the holistic perspective of the WTW emissions can reveal quite interesting results, due to the implementation of different production methods, as it is already mentioned above. So, it would be more reliable and efficient for this research, to compare the WTW emissions of all the cases and focus on how a quite novel fuel, like ammonia, can be considered a solution for the carbon

Table 2 ME-LGI ammonia consumption results from CEAS software

Load (SMCR%)	Power (kW)	Speed (r/min)	SPOC (g/kWh)	SGC (g/kWh)
100	10.240	85	8.3	346.9
95	9.728	83.6	8.6	341.5
90	9.216	82.1	9	336.6
85	8.704	80.5	9.3	332
80	8.192	78.9	9.7	330
75	7.680	77.2	10.1	328.3
70	7.168	75.5	10.6	322.2
65	6.656	73.6	11.1	316.8
60	6.144	71.7	11.7	316.7
55	5.632	69.6	12.4	316.8
50	5.120	67.5	13.3	317
45	4.608	65.1	14.2	317.3
40	4.096	62.6	15.4	317.3
35	3.584	59.9	16.8	317.7
30	3.072	56.9	18.6	316.5
25	2.560	53.5	21	315

restrictions of the coming IMO regulations, based on the WTT differences.

Furthermore, because the ME-LGI engines still emit significant amounts of NO_x, due to the low-flashpoint nature of ammonia during consumption, this engine type is typically needed to have SCR or EGR system installed. Because the scope of this research is to focus on GWP emissions, no further details regarding the utilization of such a system are included or analyzed further.

Regarding the results from CEAS software, which reveals the precious information of SFOC and SGC, it is clear in Furthermore, because the ME-LGI engines still emit significant amounts of NO_x, due to the low-flashpoint nature of ammonia during consumption, this engine type is typically needed to have SCR or EGR system installed. Because the scope of this research is to focus on GWP emissions, no further details regarding the utilization of such a system are included or analyzed further.

Tables 2 and 3 that ME-LGI can combust ammonia or MGO in a very efficient manner. The fuel consumption of MGO is 170 g/kWh, while the fuel consumption of ammonia is 346.9 g/kWh. This result could be because ammonia ignition requires about twice the volume of MGO to produce the same amount of energy.

2.3 Phase 3: results analysis

The scope of this subchapter is to describe the methodology that has been followed to reach the findings of this study and to analyze the ways that PT-LCA for ammonia can achieve

Table 3 ME-LGI MGO consumption results from CEAS software

Load (SMCR%)	Power (kW)	Speed (r/min)	SFOC (g/kWh)
100	10.240	85	170
95	9.728	83.6	167.8
90	9.216	82.1	165.8
85	8.704	80.5	164
80	8.192	78.9	163.5
75	7.680	77.2	163.1
70	7.168	75.5	160.7
65	6.656	73.6	158.8
60	6.144	71.7	159.3
55	5.632	69.6	160.1
50	5.120	67.5	161
45	4.608	65.1	162.1
40	4.096	62.6	163.2
35	3.584	59.9	164.9
30	3.072	56.9	166.1
25	2.560	53.5	167.8

quite interesting outcomes, related to the carbon footprint of the fuel.

It is a fact that WTT emissions could be the most significant phase of the LCA when ammonia fuel is the main subject. This comparison offers several ammonia production techniques to assess their relative performance and environmental impact. For the LCI part, CML 2001 is used for analyzing the results, as is shown in Table 5.

This research will also show the results of the comparison between ammonia and MGO. For making the results even more reliable, the SFOC of the MGO consumption comes from the CEAS software and particularly from the dual-fuel engine ME-LGI that is used for the ammonia study. In addition, the data regarding the GWP emissions from the WTT stage comes from Schuller (Kupferschmid and Schuller 2019), while the data for the TTW part comes from the research of Hwang (Hwang et al. 2019a, b).

One of the novelties of this research is the implementation of regression analysis to predict the potential GWP emissions from the bulk carriers that are studied. According to Cho, regression analysis is a collection of statistical methods for determining the relationships between variables (Cho and Golberg 2010). This analysis is one of the most frequently used data analysis techniques, with applications in a range of studies, including engineering. In this research, this technique is used through the PT-LCA platform, and built-in, LabView software. After the thousands of LCAs for the case studies of bulk carriers, the results related to GHG emissions are plotted. Then by using regression analysis, the final equations that could predict the GWP impact of the case studies are created. After that, the user can use these simple equations, by putting inputs related to the actual power of the bulk carrier, and as a result receive estimations regarding the potential GWP emissions of the case vessels, based on her 30-year lifespan. The results of this procedure are presented in Figs. 5 and 6.

Further analysis of the results can be found in Section 3, where the actual GWP findings of this study are presented, and further explanation of the regression analysis outcomes will be made.

3 Case study and results

This chapter intends to provide the actual findings of the PT-LCA that were conducted to identify correlations between inputs and environmental potentials for thousands of bulk carriers using regression analysis.

The next subsections will analyze further the results, by comparing not only the carbon footprint of the different production methods but also ammonia and MGO. This comparison tends to reveal the actual nature of ammonia as a marine fuel.

Table 4 Input data for tank-to-wake GWP emissions for ammonia, HFO, and MGO gases

Tank-to-wake emissions (GWP)			
Engine type	HFO engine (LSD)	Ammonia engine (ME-LGI)	MGO (ME-LGI)
Engine efficiency (J/J)	0.5 (Sharafian et al. 2019)	0.5	0.5
Fuel consumption (g/kWh)	180	346.9	170.0
Fuel consumption (MJ/kWh)	7.19 (Sharafian et al. 2019)	6.8	7.2
NOx			
g/kWh engine output	11.58 (Sharafian et al. 2019)	11.58	-
g/MJ fuel	1.61	1.61	-
kg/kg fuel	62.73	0.06273 (MAN 2020)	0.00016 (N ₂ O) (Hwang et al. 2019a, b)
CO₂			
g/kWh engine output	577 (Sharafian et al. 2019)	28.85	-
g/MJ fuel	80.14	4.007	-
kg/kg fuel	3125.4	0.0745 (MAN 2020)	3.21 (Hwang et al. 2019a, b)
CH₄			
g/kWh engine output	0.01	0.0005	-
g/MJ fuel	0.0014	0.0001	-
kg/kg fuel	0.054 (Comer et al. 2017)	0.000001 (MAN 2020)	0.00006 (Hwang et al. 2019a, b)
Lower heating value (LHV) of HFO		39 MJ/kg	
Lower heating value (LHV) of ammonia		18.6 MJ/kg	
Lower heating value (LHV) of MGO		42.7 MJ/kg	
Emission per unit of fuel energy (g/MJ fuel)		= 1/3.6×engine output (g/kWh) × engine efficiency	
Emission per mass of fuel (g/kg fuel)		= g/MJ fuel × LHV fuel (MJ/kg)	

3.1 Comparison between production methods

The comparisons that are about to be conducted are based on the power range of the vessels, because of the reliability and accuracy of the results. After conducting the PT-LCA, some very notable results have occurred regarding the WTW emissions of the several production phases, as shown in Figs. 5 and 6.

Figs. 5 and 6 are the outcomes of PT-LCA and specifically the outcomes of regression analysis mentioned in previous chapters. The data that are used as inputs, due to R-square (COD), were the power requirements of each bulk carrier, in a 30-year lifespan. After plotting the results, some quite interesting equation reveals the way that a user can predict and examine the GWP performance of a fleet of bulk carriers. The equations can be found, in detail, in the Appendix section of this study.

It is important to be noticed in Figs. 5 and 6 that the power range of the vessels has the maximum GHG emissions at 29.260 kW of power, while the minimum GWP

values are at 10.151 kW of power. That means that bulk carriers with more power needs and probably greater dead-weight are about to have the worst carbon impact than the ones with lower power needs.

Also, Figs. 5 and 6 aim to present a comparative view of the WTW emissions of the production methods when all the values that are included in these figures represent the maximum values of GWP at the power of 29.260 kW.

The PT-LCA allows analyzing the carbon impact of a fleet of bulk carriers. Particularly, the blue lines in Figs. 5 and 6 represent the resulting WTW equations of the PT-LCA. This equation allows identifying the GWP impact of the whole fleet, at any power range between 10.151 and 29.260 kW, in the simplest possible way. Eventually, it is not mandatory for someone to be expert in the field of LCA to read these figures and observe the actual WTW carbon footprint.

By using this tool, starting from the methods with less carbon dioxide equivalent emissions, it is observed that ammonia from the 3-step Cu-Cl cycle shows the most environmentally friendly trend than other ammonia production methods as the ship power increases, following ammonia from biomass downdraft gasifier and ammonia from biomass CFBG which extract the same amount of 1.128E+09 kg CO₂ Eq.

Furthermore, ammonia from electrolysis via wind with 1.420E+09 kg CO₂ Eq. and then ammonia from UCG with CCS with 1.860E+09 kg CO₂ Eq. close the loop with the

Table 5 Input data for CML 2001

Impact categories (unit)	Characterization factors	Source
GWP (kg CO ₂ Eq.)	1 CO ₂ , 28 CH ₄ , 265 N ₂ O	Stocker et al. (2013)

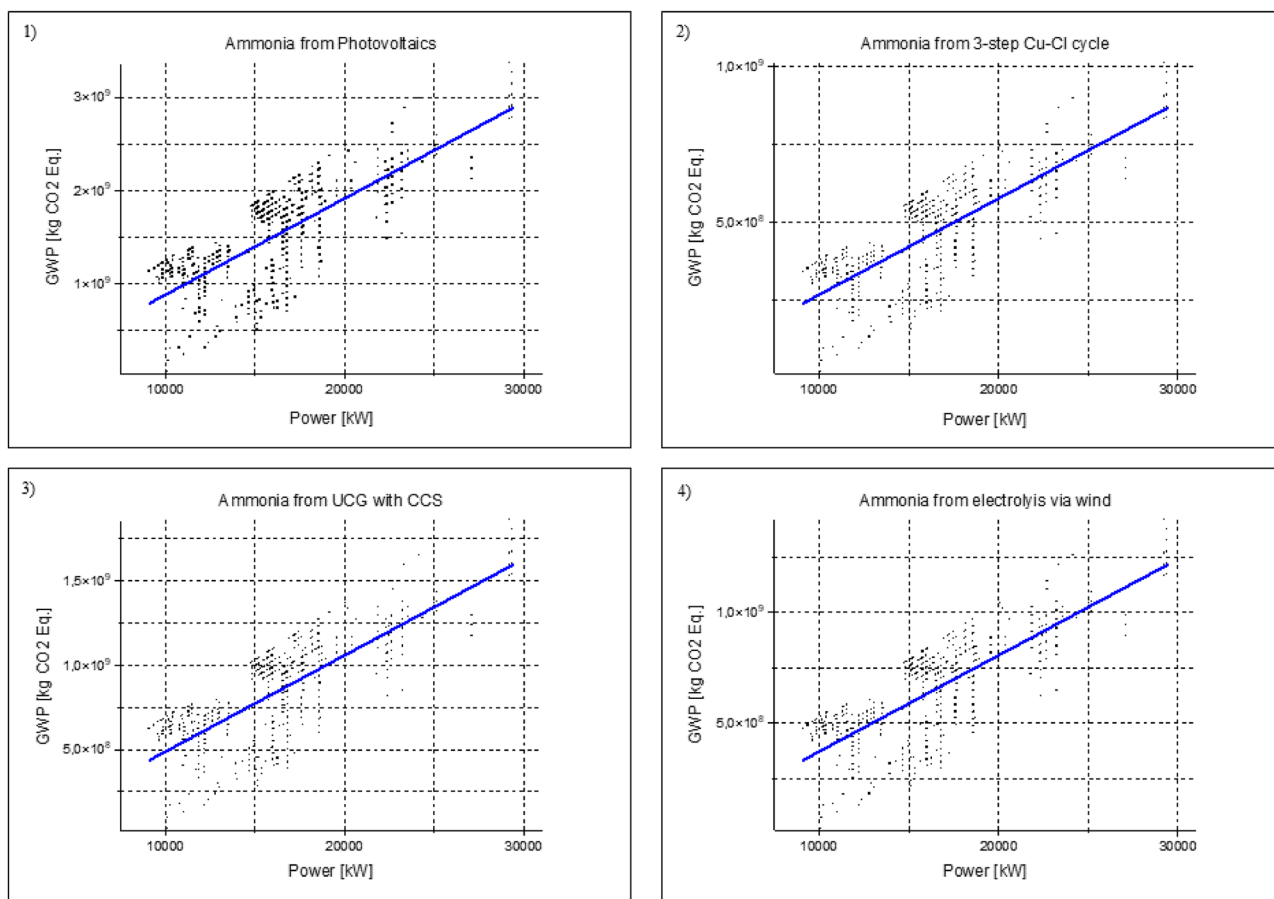


Fig. 5 WTW results for different production methods through PT-LCA describing environmental impacts (GWP) according to engine power (kW): 1) ammonia from photovoltaics, 2) ammonia from

3-step Cu-Cl cycle, 3) ammonia from UCG with CCS, 4) ammonia from electrolysis via wind

techniques which have a priority regarding the WTW carbon dioxide equivalent emissions. On the other hand, procedures like ammonia from photovoltaics with $3.366\text{E}+09$ kg CO_2 Eq. and ammonia from steam methane reforming with $7.735\text{E}+09$ kg CO_2 Eq. are more harmful to the environment than the others that are mentioned above. However, the most detrimental route is ammonia from UCG without CCS with $9.781\text{E}+09$ kg CO_2 Eq., a value last on the list with the recommendations about which could be the most feasible technique to invest in.

However, the contribution of PT-LCA to the analysis is the above numerical results that reflect the carbon footprint of a fleet of vessels. This is proof that the WTW equations that are used provide a fast, immediate, and simple overview of the GWP impact just by putting the power as an input. Otherwise, by using the classical LCA approach, the required time for the same outcome would be greater, and also the need for expertise would be significant.

The results presented the GWP impact of bulk carriers from a WTW perspective and proved that the power needs of

the vessel are the key to evaluating the most carbon-friendly approach to producing ammonia. The outcomes can be used as a quantitative measure for stakeholders that allow them to choose which pathway could emit the most or least carbon emissions according to their vessel's needs of power. A clear presentation of the WTW outcomes according to each production method can be seen in Fig. 7.

3.2 Comparison between MGO and ammonia

This subsection aims to present a comparison between ammonia and MGO from the perspective of WTW carbon footprint. As mentioned above, the power needs of the vessels could be the core measure to evaluate which production pathway is more carbon-friendly for ammonia. However, when other fuels like MGO are compared with ammonia from a WTW perspective, some quite interesting results can be observed in Fig. 8.

According to the analysis of Fig. 8, bulk carriers that combust MGO extract $4.720\text{E}+09$ kg CO_2 Eq., when the

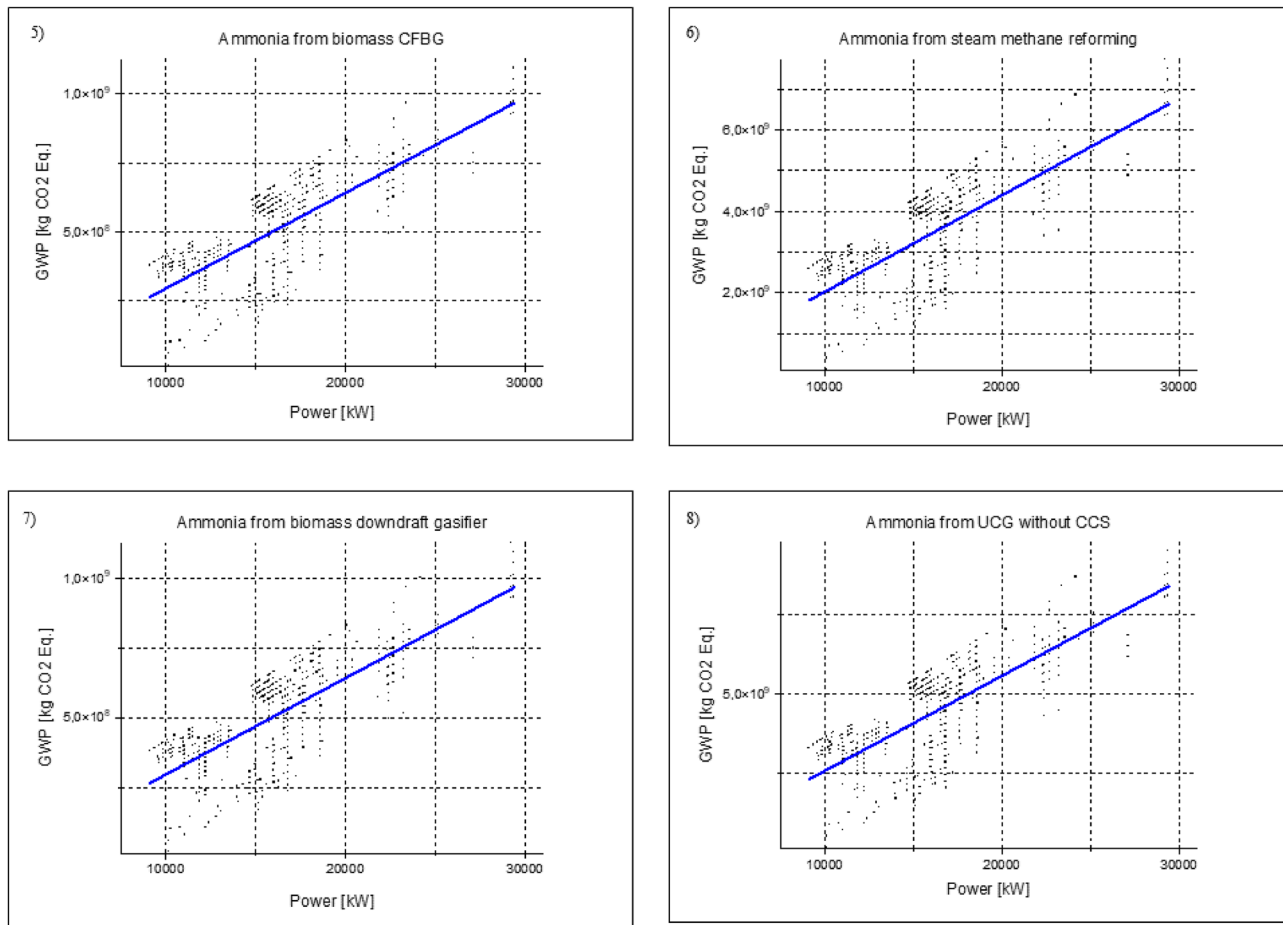


Fig. 6 WTW results for different production methods through PT-LCA describing environmental impacts (GWP) according to engine power (kW): 5) ammonia from biomass CFBG, 6) ammonia from

steam methane reforming, 7) ammonia from biomass downdraft gasifier, 8) ammonia from UCG without CCS

power need of the vessels is 29.260 kW, and 5.849E+07 kg CO₂ Eq. when the power need is 10.151 kW. Eventually, it would be inefficient to compare the case of MGO with all the ammonia cases that are already mentioned. The reason is that only ammonia from steam methane reforming, ammonia from photovoltaics, and ammonia from UCG without CCS can show the actual position of MGO in the carbon hierarchy of this research.

The results divulged something very absorbing regarding the WTW emissions of MGO and ammonia. As noted in Fig. 9, MGO with 4.720E+09 kg CO₂ Eq. is preferable to ammonia from steam methane reforming with 7.735E+09 kg CO₂ Eq. and ammonia from UCG without CCS with 9.781E+09 kg CO₂ Eq. However, it extracts more GHG pollutants than ammonia from photovoltaics with 3.366E+09 kg CO₂ Eq.

As it is easily observed, ammonia is not as innocent as it may seem. Current fuels like MGO can be replaced with ammonia, but only when the production method and eventually WTT carbon emissions are more ecological feasible. In

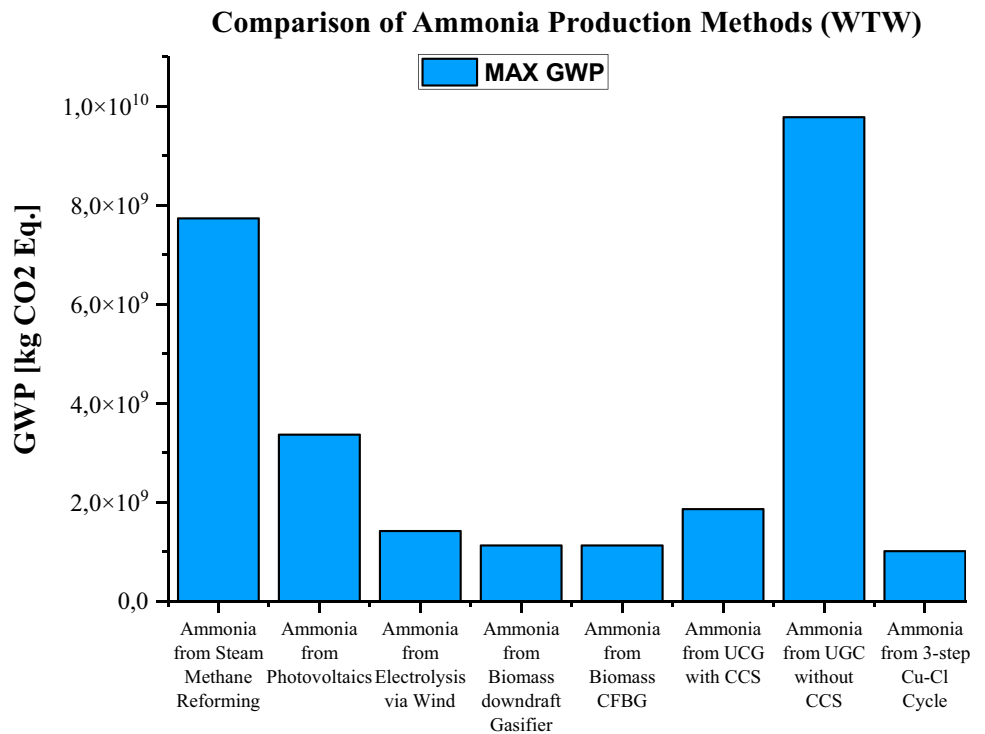
this case, the actual difference between these fuels comes from the ammonia ignition procedures that require about twice the volume of MGO to produce the same amount of energy, and from the production method of MGO in the distilleries. The 3-step Cu-Cl cycle remains the most carbon-friendly approach to producing ammonia.

4 Discussion

It is a fact that ammonia can be considered one of the potentials “holy grails” for adapting the coming regulations for 2050 and reducing more than 50% of the GHG compared with 2008 standards. Currently, fuels like HFO or MGO are more harmful than ammonia, considering their carbon impact not only during their consumption but also during the production phase.

Nowadays, the maritime sector faces a lack of well-established regulations and guidelines that can be used as a pathway for new alternative sources of energy and

Fig. 7 Comparison between ammonia production methods regarding WTW emissions



fuels. The need for an LCA-based methodology is more vital than ever since it is the only way, for the maritime industry, to deal with future restrictions from IMO. The PT-LCA methodology can be used as a tool that can fill this gap in the industry and helps the conduction of a new framework that will allow fuels like ammonia to be applicable and approachable in the most feasible way.

The PT-LCA was developed to provide a viable solution to such challenges. To fill the research gap, this work employed the PT-LCA to examine broad patterns of the carbon footprint of ammonia as fuel, as well as considerable data for thousands of bulk carriers traveling worldwide. This novel methodology enables to compressing of all the complicated and inconsistent data on the carbon footprint

Fig. 8 WTW results for MGO through PT-LCA describing environmental impacts (GWP) according to engine power (kW)

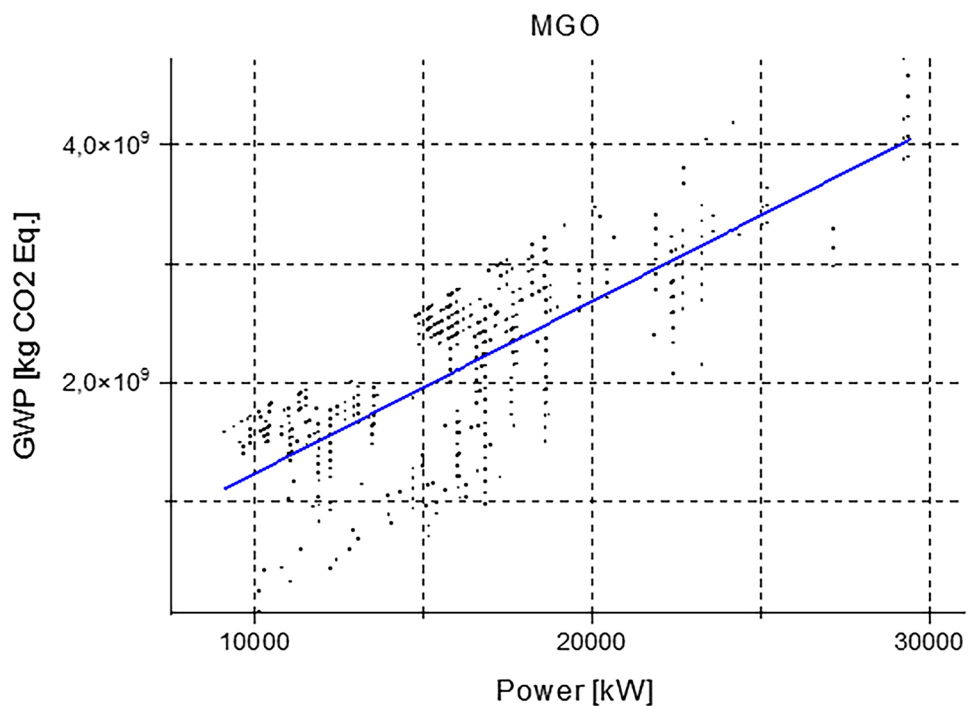
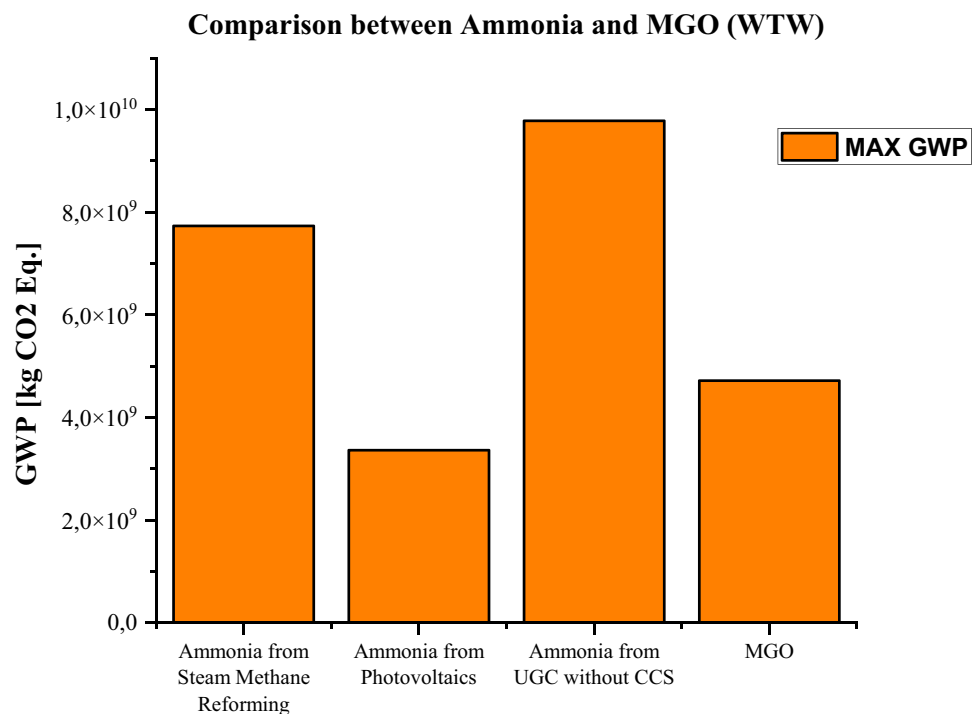


Fig. 9 Comparison between ammonia and MGO regarding WTW emissions



of ammonia as a marine fuel into simple equations. These equations can be expressed as correlations between inputs (vessel specifications) and outcomes (GWP impact). Without any knowledge of LCA, which is sometimes inaccessible for research, this style of results might be helpful to quickly comprehend whether using ammonia is ultimately a superior fuel option for the near future. In truth, it will be a handy tool for quick comparisons, although it condenses a significant amount of information on novel engine types, like ME-LGI, and ship parameters. These are the reasons why PT-LCA and specifically regression analysis can contribute to a more decarbonized future.

Currently, the formulas of PT-LCA that estimate the GWP indicator still need further development. This fact can be proved by observing the *R*-square value which is near 60% (Appendix). The reason hides inside the integration procedures because when a significant amount of information is utilized, eventually some data will probably be lost. Specifically, in cases like ammonia that are still under development, the user should be aware of this, because there is still some lack of data due to the novelty of this fuel. Using this methodology is vital to have plenty of data that can be used to estimate the environmental indicators. Specifically, for this case study, the estimation of fuel consumption (SFOC and SGC) is still claimed by functional units. If these data are not readily available, those units will not be utilized to compare environmental performance between vessels and novel engines like ME-LGI.

Even though PT-LCA has the limitations discussed above, it is important and necessary for the maritime industry. It

can be utilized as a tool that contributes significantly to the development of an environmental regulatory framework for the maritime industry from a life cycle perspective. Anyone who has access to data can choose and utilize PT-LCA. There is no need for LCA expertise to use PT-LCA, so this is the core advantage of this methodology compared to other and the traditional LCA. For the case study of ammonia, it may be difficult to apply the findings to all the bulk carriers separately. In terms of projecting the future thoroughly by detecting the general trend, PT-LCA may be more practical and extensively used than the current LCA. Eventually, PT-LCA surpasses its limitations and contributes as an efficient approach to developing the regulatory framework of the industry.

Regarding the WTT, TTW, and WTW emissions of ammonia, it is quite clear that by equipping all the case vessels with the same ME-LGI engine, the most important aspect which determines how carbon-friendly is the production phase of ammonia. By choosing and investing in a suitable technique, GHG can be reduced significantly and WTW emissions adapt to the IMO restrictions.

5 Conclusion

Following the discussion of the results that are found in the previous chapters, a more quantitative perspective of the results that this research deal with is about to be presented.

It is observed that the carbon footprint is directly proportional to the vessel's power. The proposed formula in the

Appendix can be used to find out more about the relationships. These formulas will serve as rapid indications for comparing the overall carbon impact of thousands of bulk carriers equipped with the ME-LGI engine, carrying ammonia as fuel from different production methods. These equations represent the actual novelty of the PT-LCA method. Specifically, they can be implemented by shipowners, classification societies, policymakers, and other stakeholders from the maritime industry, as a quite useful tool that could predict the carbon impact of ammonia as a fuel. Eventually, PT-LCA could be a core decision-making tool that can contribute to the formation of a framework or policy that can allow alternative fuels, like ammonia, to enter the maritime industry and have a significant role as a carbon-friendly solution.

For estimating the carbon impact of ammonia as marine fuel from a well-to-wake (WTW) perspective, it is mandatory to focus on the well-to-tank (WTT) phase. Specifically, due to the absence of ammonia engines in the shipping industry, only assumptions based on ME-LGI engines can be made, and the actual parameter that contributes to the carbon performance of ammonia as fuel is the production method. However, further attention needs to be taken because current fuels like MGO may produce less WTT emissions than some of the ammonia production cases.

In future work, PT-LCA can be applied more widely to alternative marine fuels such as hydrogen and methanol. Similarly, the environmental advantages of their shipping activities are undervalued. The suggested LCA technique is also expected to explain their strengths and drawbacks as future maritime fuels. As a result, a series of future studies should be conducted to establish the optimal energy source for long-term shipping. Aside from the environment, PT-LCA should be used to address a variety of societal issues. Furthermore, more applications of PT-LCA regarding ammonia fuel can be conducted on different types of vessels like tankers, containerships, and Ro-Ro. It will be beneficial

for any subject requiring a comprehensive approach, such as the economy or safety. The outcomes of the research can help the industry confirm the best option in many situations, which is expected to have a significant impact on future energy policies and regulatory frameworks.

The summary of all the novel characteristics that are already mentioned in this study is as follows:

- Plan and exhibition of the superiority of an updated LCA technique in addressing current assessment difficulties and limitations provided by existing marine carbon indicators and traditional LCA methodologies.
- Demonstrating the potential strength of the novel LCA technique, which contains substantial benefits from its capabilities for investigating and addressing various industrial challenges for economic, environmental, and safety concerns.
- To investigate the carbon impact of using ammonia as a future maritime fuel, providing clear and quantifiable information on what conditions bulk carriers may profit from ammonia and what situations they should not be necessary.
- It provides a method to make LCA more widely applicable in maritime applications. Furthermore, it helps to address a basic problem in the LCA method while also making it more accessible to anybody interested in analyzing the environmental consequences of GWP when utilizing ammonia as a maritime fuel without the need for specialist assistance.

Appendix

The Appendix presents the summary of WTW emissions for ammonia under various production scenarios as forms of indicators (equations).

Table 6 Equations of WTW estimation for ammonia from 3-step Cu-Cl cycle

Phase	Equation	Residual sum of squares	Pearson's r	R -square (COD)	Adj. R -square
Production (WTT)	$y(GWP) = 25364,69039 + (-3,65742E7) * x$	9.61959E18	0.77582	0.60189	0.60169
Operation (TTW)	$y(GWP) = 5688,77414 + (-8202833,00559) * x$	4.83877E17	0.77582	0.60189	0.60169
Overall (WTW)	$y(GWP) = 31053,46452 + (-4,4777E7) * x$	1.44184E19	0.77582	0.60189	0.60169

Table 7 Equations of WTW estimation for ammonia from biomass CFBG

Phase	Equation	Residual sum of squares	Pearson's r	R-square (COD)	Adj. R-square
Production (WTT)	$y(GWP) = 28885,0621 + (-4,16503E7) * x$	1.24751E19	0.77582	0.60189	0.60169
Operation (TTW)	$y(GWP) = 5688,77414 + (-8202833,00559) * x$	4.83877E17	0.77582	0.60189	0.60169
Overall (WTW)	$y(GWP) = 34573,83623 + (-4,98532E7) * x$	1.78728E19	0.77582	0.60189	0.60169

Table 8 Equations of WTW estimation for ammonia from biomass downdraft gasifier

Phase	Equation	Residual sum of squares	Pearson's r	R-square (COD)	Adj. R-square
Production (WTT)	$y(GWP) = 28885,0621 + (-4,16503E7) * x$	1.24751E19	0.77582	0.60189	0.60169
Operation (TTW)	$y(GWP) = 5688,77414 + (-8202833,00559) * x$	4.83877E17	0.77582	0.60189	0.60169
Overall (WTW)	$y(GWP) = 34573,83623 + (-4,98532E7) * x$	1.78728E19	0.77582	0.60189	0.60169

Table 9 Equations of WTW estimation for ammonia from electrolysis via wind

Phase	Equation	Residual sum of squares	Pearson's r	R-square (COD)	Adj. R-square
Production (WTT)	$y(GWP) = 37834,07294 + (-5,45542E7) * x$	2.14024E19	0.77582	0.60189	0.60169
Operation (TTW)	$y(GWP) = 5688,77414 + (-8202833,00559) * x$	4.83877E17	0.77582	0.60189	0.60169
Overall (WTW)	$y(GWP) = 43522,84707 + (-6,2757E7) * x$	2.83225E19	0.77582	0.60189	0.60169

Table 10 Equations of WTW estimation for ammonia from photovoltaics

Phase	Equation	Residual sum of squares	Pearson's r	R-square (COD)	Adj. R-square
Production (WTT)	$y(GWP) = 97508,64801 + (-1,40601E8) * x$	1.42162E20	0.77582	0.60189	0.60169
Operation (TTW)	$y(GWP) = 5688,77414 + (-8202833,00559) * x$	4.83877E17	0.77582	0.60189	0.60169
Overall (WTW)	$y(GWP) = 103197,42214 + (-1,48804E8) * x$	1.59234E20	0.77582	0.60189	0.60169

Table 11 Equations of WTW Estimation for Ammonia from steam methane reforming

Phase	Equation	Residual sum of squares	Pearson's r	R-square (COD)	Adj. R-square
Production (WTT)	$y(GWP) = 231454,5172 + (-3,33742E8) * x$	8.00993E20	0.77582	0.60189	0.60169
Operation (TTW)	$y(GWP) = 5688,77414 + (-8202833,00559) * x$	4.83877E17	0.77582	0.60189	0.60169
Overall (WTW)	$y(GWP) = 237143,29134 + (-3,41945E8) * x$	8.40851E20	0.77582	0.60189	0.60169

Table 12 Equations of WTW estimation for ammonia from UCG with CCS

Phase	Equation	Residual sum of squares	Pearson's r	R-square (COD)	Adj. R-square
Production (WTT)	$y(GWP) = 51337,73642 + (-7,40256E7) * x$	3.94068E19	0.77582	0.60189	0.60169
Operation (TTW)	$y(GWP) = 5688,77414 + (-8202833,00559) * x$	4.83877E17	0.77582	0.60189	0.60169
Overall (WTW)	$y(GWP) = 57026,51056 + (-8,22284E7) * x$	4.8624E19	0.77582	0.60189	0.60169

Table 13 Equations of WTW estimation for ammonia from UCG with CCS

Phase	Equation	Residual sum of squares	Pearson's <i>r</i>	R-square (COD)	Adj. R-square
Production (WTT)	$y(GWP) = 294179,2669 + (-4,24187E8) * x$	1.29396E21	0.77582	0.60189	0.60169
Operation (TTW)	$y(GWP) = 5688,77414 + (-8202833,00559) * x$	4.83877E17	0.77582	0.60189	0.60169
Overall (WTW)	$y(GWP) = 299868,04104 + (-4,3239E8) * x$	1.34449E21	0.77582	0.60189	0.60169

Author contribution Ioannis Chalaris: performed the literature search and data analysis, visualization, writing—original draft, writing—review, and editing. Hayoung Jang: formal analysis, methodology, writing—review, and editing. Byoung Jeong: conceptualization, supervision.

Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors declare no competing interests.

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