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A framework for determining the life cycle GHG emissions of fossil marine fuels in countries reliant on imported energy through maritime transportation: A case study of South Korea

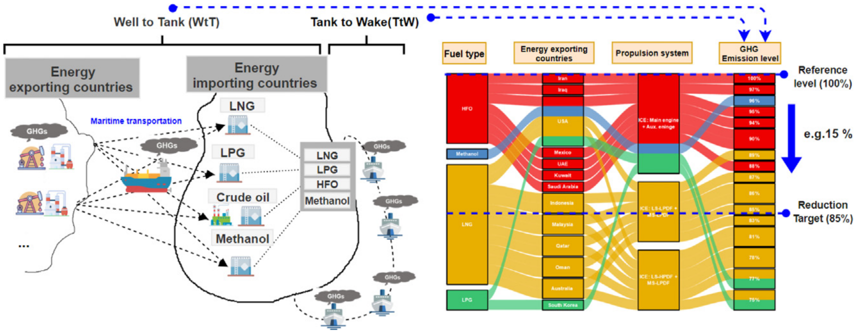
Seungman Ha [a,b,c], Byongug Jeong [a,c], Hayoung Jang [a,c], Chybyung Park [a,c,*], Byungchurl Ku [b]

[a] Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, 100 Montrose Street, Glasgow G4 0LZ, UK
[b] Korean Register, 36 Myeongji Ocean City 9-ro, Gangseo-gu, Busan, Republic of Korea
[c] Europe-Korea Marine and Ocean Engineers Association (EKMOA), 90 Cowley Close, Southampton, Hants SO16 9WE, UK

HIGHLIGHTS

- Developed framework for baseline of life cycle GHG emissions from marine fuels
- Demystified the current LCA framework for highlighting the potential impact of WtT areas neglected in regulation
- Compared the WtW emissions of selected marine fuels imported to South Korea
- Provided insights for future policies to reduce life cycle GHG emissions

GRAPHICAL ABSTRACT



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ABSTRACT

This research was motivated to address limitations in the current lifecycle assessment frameworks with the absence of proper guidelines for developing default lifecycle values of energies in consideration of supply chain activities and maritime transportation. Given this, it aims to evaluate the level of life cycle GHG emissions of heavy fuel oil, LNG, LPG and methanol as marine fuels produced and supplied in energy import-dependent countries, using South Korea as a case study. The analysis clearly shows that the impact of international shipping on Well-to-Tank (WtT) GHG emissions for energy carriers would be subject to several factors: propulsion system types, the quantify of energy transported, and the routes and distances of voyages. For instance, transportation emissions from LNG carriers for LNG fuel vary significantly depending on the country of import, ranging from 2.26 g CO_2 eq./MJ (representing 12.2 % of Well-to-Tank (WtT) emissions for Malaysia) to 5.97 g CO_2 eq./MJ (representing 33.3 % of WtT emissions

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Abbreviations: AD, average days at sea per year; AER, Annual Efficiency Ratio; A-LCA, attributional LCA modelling; AML, kilowatts (kW) at average main and auxiliary engine load; AP-X, C3MR-Nitrogen hybrid cycle; C3MR, propane precooled mixed refrigerant; $CfCO_2$, conversion factor between selected fuel consumption and CO_2 emission (t CO_2/t fuel); $CfCH_4$, methane emission factor (t CH_4/t fuel); CfN_2O, nitrous oxide emission factor (t N_2O/t fuel); CH_4, methane; CII, Carbon Intensity Indicator; C-LCA, consequential LCA modelling; CO_2, carbon dioxide; CO_2eq, carbon dioxide equivalent emissions; DCS, data collection system; DMR, dual mixed refrigerant; E, estimated annual emission amount (t); EEDI, Energy Efficiency Design Index; EEOI, Energy Efficiency Operational Indicator; EEXI, Energy Efficiency Existing Ship Index; EFGHG, TtW GHG emission factor (t/t fuel); GHG, greenhouse gases; FC, fuel consumption (t); FCprimary, primary fuel consumption (t) for main engine; FCpilot, pilot fuel consumption(t) for main engine; FCaux, fuel consumption (t) for auxiliary engine; GFS, GHG Fuel Standard; HFO, Heavy Fuel Oil; ICAO, International Civil Aviation Organization; IMO, International Maritime Organization; LCA, life cycle assessment; LCAF, lower carbon aviation fuels; LHV, lower heating value; LNG, liquefied natural gas; LPG, liquefied petroleum gas; LSD, low-speed diesel cycle engines; LS-LPDF, low-speed low-pressure dual-fuel engines; LS-HPDF, low-speed high-pressure dual-fuel engines; LSFO, low sulphur fuel oil; MARPOL, The International Convention for the Prevention of Pollution from Ships; MBMs, market-based measures; MCR, Maximum Continuous Rating; MDO, marine diesel oil; MGO, marine gas oil; MSD, medium-speed diesel cycle engines; MS-LPDF, medium-speed low-pressure dual-fuel engines; N_2O, Nitrogen Oxides; NCR, Normal Continuous Rating; NGLs, natural gas liquids; SAF, sustainable aviation fuels; SFOC, specific fuel consumption (g/kWh) for primary fuel at AM; SPOC, specific fuel consumption (g/kWh) for pilot fuel at AML; SEEMP, Ship Energy Efficiency Management Plan; SMR, single mixed refrigerant; TtW, Tank-to-Wake; UNFCCC, United Nations Framework Convention on Climate Change; WtT, Well-to-Tank; WtW, Well-to-Wake.

[*] Corresponding author at: Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, 100 Montrose Street, Glasgow G4 0LZ, UK.
E-mail address: chybyung.park@strath.ac.uk (C. Park).

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for Qatar). As a preliminary study, an enhancement on the quality of the input/inventory data is imperative for obtaining a reliability of results. Nevertheless, the comparative analysis of different fuels and life stages provides valuable insights for stakeholders to develop effective policies and energy refueling plans for reducing life cycle GHG emissions from marine fuels. These findings could also enhance the current regulatory framework and provide meaningful lifecycle carbon footprints of marine fuels for energy importing countries. The study results also strongly suggest that default values of GHG emission for different countries relying on energy imports via international maritime transport should be further developed in consideration of the impact of regional differences, such as distance, from the importing country for successful arrival of LCA application on marine industry.

1. Introduction

This Section provides an overview of the current issues with the IMO LCA regulatory framework on marine fuels. It also discusses challenges related to national and regional LCA regulatory frameworks for marine fuels. Lastly, the section outlines the research objectives and contributions of this study.

1.1. Background

In international trade, maritime transport is considered the most efficient means to transport cargo and passengers overseas compared to other modes such as air, rail or road (Lenzen et al., 2023). Global GHG emissions from shipping activities account for about 3 % of global annual CO_2 emissions equivalent to the amount of annual CO_2 emissions in Germany, the world 6th largest emitter (Yuan et al., 2023). The emission level from international shipping is highly expected to increase from 50 to 250 % by 2050 depending on economic and energy scenarios (IMO, 2020). To improve ships' energy efficiency while reducing CO_2 levels, the International Maritime Organization (IMO) adopted the first-ever legally binding instrument entitled "Regulations on energy efficiency for ships" to MARPOL Annex VI in 2013. This package consists of technical and operational instruments which are known as the Energy Efficiency Design Index (EEDI) for new-built ships, and the Ship Energy Efficiency Management Plan (SEEMP) for all ships. For evaluation of ship energy efficiency and CO_2 emissions from ship operation, the SEEMP proposes the use of a voluntary monitoring tool named Energy Efficiency Operational Indicator (EEOI) for each ship. With the adoption of *the IMO Initial GHG Strategy* in 2018, the IMO set a new target at CO_2 reduction per transport work by at least 40 % by 2030 compared to the 2008 level while pursuing toward 70 % reduction by 2050, in parallel with the total 50 % GHG emission reduction in quantity by 2050 (IMO, 2018b). More recently, in 2021, the IMO has introduced a series of additional technical measures: the Energy Efficiency Existing Ship Index (EEXI) for existing ships and several different types of Carbon Intensity Indicators (CIIs) like Annual Efficiency Ratio (AER), Energy Efficiency Operational Indicator (EEOI), and other CIIs for implementing a rating scheme as operational measure (IMO, 2022d). As a basket of candidate mid-term GHG reduction measures, the market-based measures (MBMs) have been also considered with combination of those technical measures such as a GHG fuel standard or IMO's carbon intensity measures (IMO, 2022b).

Despite the ambitious goals for reduction in GHG emissions established by the IMO, the introduction of alternative fuels to the shipping industry still remains at their brevity, as illustrated in Fig. 1.

1.1.1. Current issues on IMO LCA regulatory framework on marine fuels

The aforementioned IMO regulations and indicators aiming to curb air pollution are highly skewed by CO_2 emissions from shipping activities. Despite vigorous efforts of the IMO and its Member States, waterborne transportation keeps contributing to the increment in emission levels by imposing greater burdens on other energy sectors. For example, the higher demand for hydrogen produced from natural gas for marine vessels reduces emissions in the shipping sector, but increases emissions in the energy production sector.

However, the current energy efficiency indexes established by the IMO, including EEDI, EEXI, AER and EEOI, have a limitation on evaluating the holistic GHG emission impact on marine fuels as they only consider emissions from ships and not the entire lifecycle of the fuel. To remedy current challenges while enhancing sustainability across sectors, IMO has proposed an urgent workstream for developing *"lifecycle GHG/carbon*

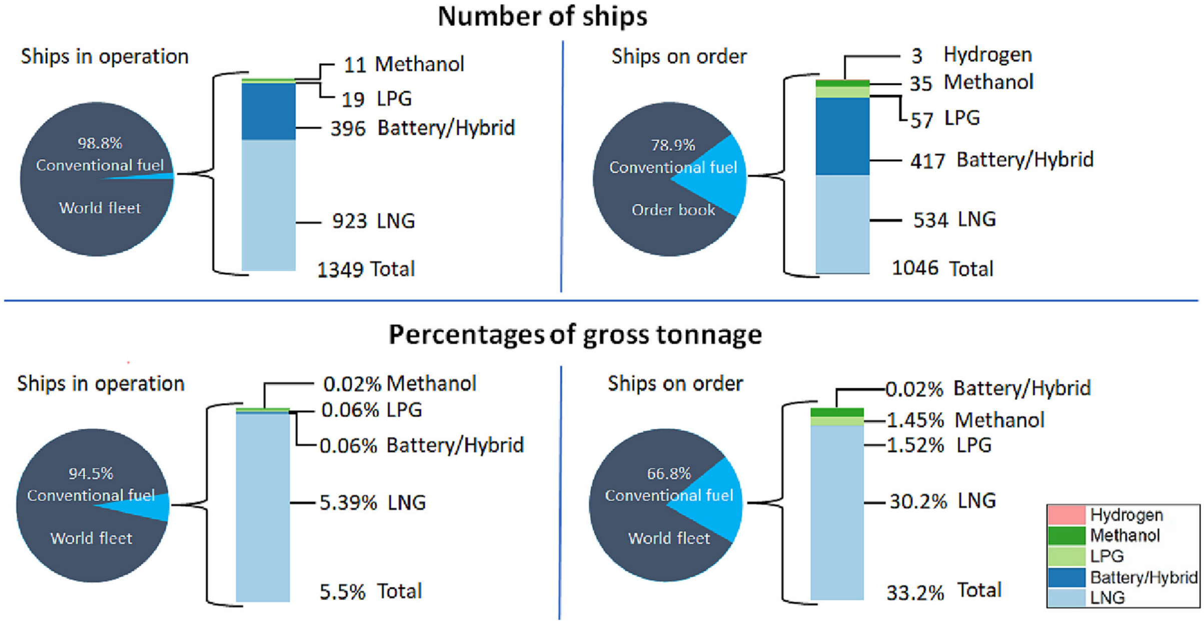


Fig. 1. Alternative fuel uptake in the world fleet by number of ships (DNV, 2022).

intensity guidelines for marine fuels" with the primary work scope to develop Well-to-Tank (WtT) emission factor and Tank-to-Wake (TtW) default emission factors for marine fuels (IMO, 2018b). Nevertheless, due to the lack of unified LCA methodologies for marine fuels, a series of challenges are encountered in a process of developing robust default emission values. These emission factors in these guidelines are likely to be used as key inputs for enhancing the current IMO energy efficiency frameworks associated with EEDI, EEXI, CII and other instruments. Fig. 2 shows credible scenarios - identified in this research work - through which the scope of lifecycle analysis on marine fuels can be proposed in multiple ways such as well-to-wake (WtW), well-to-tank, or tank-to-wake scopes.

The current IMO LCA framework considers introducing fuel certification schemes through new guidance on verification and certification for actual GHG emissions from different marine fuels. It is intended to grant flexibility in industrial choices and to incentivize the lower GHG emission fuels than the default values proposed in the LCA guidelines. This approach can allow fuel suppliers and ship operators to use actual emission values rather than default ones, while third-party verification and certification could also accommodate regional differences and specific feedstock. However, the absence of robust WtT and TtW emission default values, anticipated to be developed by a unified LCA methodology, may hinder the rule makers to apply the LCA approach to the maritime industry. Robust default values for those marine fuels being widely used by the world fleet will play a crucial role in not only identifying the emission levels of marine fuels, helping set achievable targets for decarbonization in the shipping sector but also incentivizing GHG reductions in lifecycle footprint across the fuel supply chain. In other words, especially for conventional marine fuels, it is an urgent issue to develop robust WtT and TtW emission values through a unified methodology.

Another issue in determining robust default emission values lies on the uncertainties and variations stemming from difference in geographical locations across nations and their supply routes and methods. Importantly, it needs to be clarified how to tackle the geographical aspects in developing default emission factors for marine fuels for WtW emission. For instance, the lifecycle impacts of LNG supplied within LNG producing countries would be significantly different from the same volume of LNG imported from distant countries either by ship or road (IMO, 2022a). On the other hand, Norway et al. argued that the GHG impacts caused by fuel import/export activities from and to different nations/regions are negligibly small, while insisting that larger variations in the GHG intensity could fall into the electricity mix across regions producing synthetic fuels (IMO, 2021). The identification and characterization of geographical differences in developing default emission factors for marine fuels is a crucial research gap that needs to be addressed.

1.1.2. Challenges on national and regional LCA regulatory framework for marine fuels

From a national and regional regulation perspective, the European Union (EU), the most proactive bloc for curbing GHG, has established the FuelEU Maritime initiative that proposes the introduction of lifecycle GHG impacts of maritime fuels; not only limiting the GHG intensity driven from onboard fuel consumptions, but also using a lifecycle analysis when assessing their GHG intensity (Marketa, 2022). A challenge can be observed through the fact that energy resources are not necessarily produced within the bloc or their own countries. It implies that there still require significant efforts to propose a unified LCA method and relevant data applicable to the EU initiative. Lack of clarification would leave greater challenges behind the rest of the world which are highly influenced by the EU's environmental policy. As a result, it is paramount to grasp the GHG footprint of those fuels by all countries; it is obvious that different countries have different levels of GHG impacts on marine fuels. For instance, South Korea's energy environment heavily relies on energy imports from handful energy producing countries. It accounts for approximately 98 % of the national fossil fuel demand, wherein 70 % of Korea's petroleum was shipped from the Middle East in 2019 (U.S. Energy Information Agency, 2019). Like South Korea, countries that are highly subject to energy import such as Japan, Taiwan or others, need wider energy policies to achieve lifecycle decarbonization by tracking fuel types, applied production methods, and supply chains of fuels from

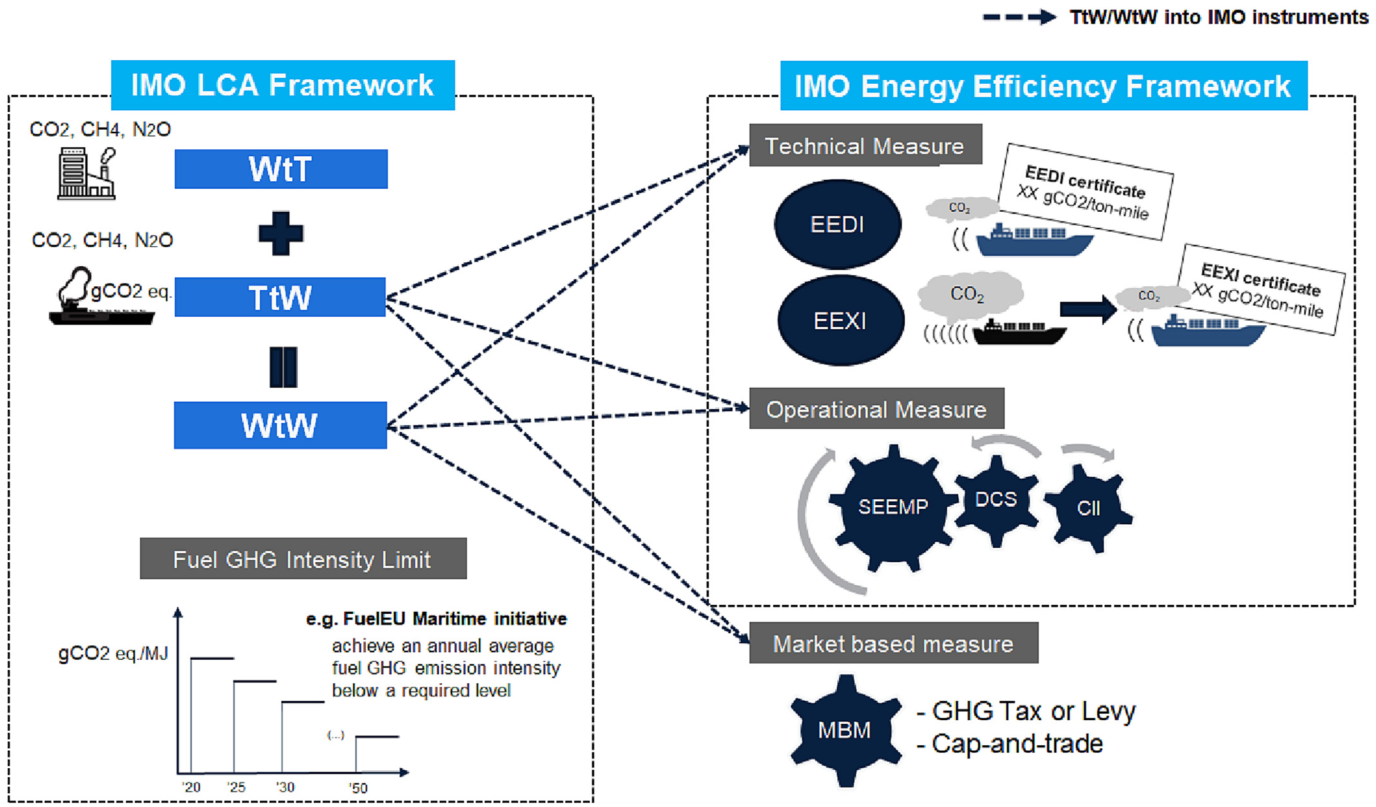


Fig. 2. Overview of credible IMO LCA applications to existing regulatory frameworks.

exporting places. In line with this, South Korea has introduced the national hydrogen economy roadmap for promoting hydrogen as a key national energy source. It targets not only decarbonization for all industry sectors but also the production and distribution of hydrogen. The roadmap also includes the future plan for overseas imports of green hydrogen from Australia and some others by 2030 (Kim et al., 2023). In this aspect, to assess the effectiveness of lifecycle policies aimed at promoting cleaner energy sources, it is imperative to establish a baseline of lifecycle GHG emissions associated with conventional fossil fuels. Such a baseline can serve as a reference point for comparison with alternative fuels, allowing for a quantitative evaluation of the success of these policies in reducing overall GHG emissions.

Against the backdrop of mounting environmental concerns, policymakers have evinced growing interest in substituting conventional fossil-based fuels with alternative fuels in the marine sector. However, there has been a relative lack of effort from a policy perspective to determine the present state of life cycle GHG emissions, which is vital to evaluate the effectiveness of lifecycle policies toward cleaner energies. To address this gap, it is crucial to develop reliable default WtW emission values of marine fuels and establish a database tailored to specific countries and circumstances. Such efforts can inform the formulation of future policies aimed at promoting sustainable and renewable fuels in the shipping sector.

1.2. Research objective and contribution

This study aims to address two key research questions: How should default GHG life cycle emission values for marine fuels be determined in import-dependent countries? And, to what extent do regional or geographic differences impact the GHG lifecycle emission values of marine fuels, such as emissions from maritime transportation? The importance of these questions lies in the significant environmental impact of maritime transportation and its contribution to global GHG emissions, which are a key driver of climate change.

In this context, this paper contributes to the literature and arrival of LCA to the shipping sector by achieving the following objectives: (1) to develop a model to calculate the present WtW emission level of conventional marine fuels produced and supplied in energy import-dependent countries, with a case study of South Korea; (2) to evaluate how the geographic difference influences on the overall WtW emission through case study; (3) to contribute to the development of robust default emission values based on fossil fuels in the LCA regulatory framework; and (4) to help a government establish future regulatory target based on WtW emission level of conventional fuels. To the best of the authors' knowledge, this study is first attempt to setting the default GHG emission value of marine fuel from a policy perspective of energy importing countries (i.e. South Korea). The contribution to future national and regional LCA regulatory framework of this study will be highlighted in discussion of Section 5.

To address the research questions, this paper is organized as follows: Section 2 reviews relevant literature that examined the life cycle GHG emissions of marine fuels, identifying gaps in the research related to the determination of default GHG life cycle emission values for marine fuels from the perspective of energy-importing countries like South Korea. Section 3 explains the main materials and methods used in this study. Section 4 presents the study's overall results, including an analysis of the impact of maritime transportation on the lifecycle emission levels. In Section 5, we discuss the implications and limitations of our findings. Finally, Section 6 summarizes the key conclusions.

2. Literature review

Voluminous studies have been conducted to evaluate and compare the environmental performance of several marine fuels from a life cycle perspective as summarized in Table 1. In the literature, three key pollutants - CO_2, CH_4, and N_2O - were mainly considered within the GHG emission scope in the analysis since these three gases are the most significant contributors to overall GHG emissions. However, previous studies have self-demonstrated that there is no unified LCA approach to the fundamental methodology for estimating GHG emissions. As a result, research outcomes were subject to high ambiguity due to the lack of unified analysis scope, case study, assumptions, data usage, etc. In the LCA modelling, the selection of the attributional and consequential LCA (referred to as A-LCA and C-LCA) is a crucial element that greatly influences the determination of default emission values. Despite this fact, few LCA studies on marine fuels have clearly presented their methodologies; either attributional or consequential LCAs. A-LCA modelling simply describes the immediate physical flows (e.g., energy, emissions and material) throughout the life cycle of a product and its subsystems. On the other hand, C-LCA modelling further considers how physical flows can be modified in response to changes in product demands with possible decisions (Chester and Cano, 2016; Earles and Halog, 2011; Moretti et al., 2022a; Moretti et al., 2022b; Vázquez-Rowe et al., 2014).

A review of literature on the topic of C-LCA and A-LCA reveals a diverse range of perspectives on the advantages and disadvantages of these two methodologies. Studies by (Brandão et al., 2014; Dale and Kim, 2014; Ekvall, 2019; Hertwich, 2014; Plevin et al., 2014; Prapaspongsa and Gheewala, 2017; Schaubroeck et al., 2021; Zamagni et al., 2012) have all contributed to this discourse, highlighting various pros and cons associated with each approach. Despite this, it is worth noting that the aviation sector similar to the shipping sector adopted a process-based attributional LCA approach along the whole aviation fuel supply chain (ICAO, 2019). Also, the LCA regulatory framework for marine fuels should clearly define the unified selection of A-LCA and C-LCA.

With regard to variations in GHG emission impacts from the production and transportation of marine fuels across different regions, a number of studies have neglected to consider the sensitivity of GHG emissions from the maritime transportation and distribution of these fuels. These studies either focus on specific cases or do not address the impact of maritime transportation, making it challenging to use them as default values for policymaking. As demonstrated in Table 1, several studies have used default emission values for maritime transportation, as provided by the GREET or GaBi models. The fuel consumption in the GaBi model was estimated as linear or quadratic polynomial functions of ship's deadweight. In addition, several studies have used default emission values for energy transport by certain ships or from specific regions in their analyses. For instance, the study conducted by (Hwang et al., 2019) has limited scope, focusing primarily on MGO refined through crude oil imported from Qatar and the United States, and LNG from Qatar and the United States. It also employed genetic equations that show the relationship between emission levels and distance traveled with a certain level of cargo. However, it's important to note that these emission models are not only based on the actual operation data of the ship but also on the overall energy import status of the importing countries. On the other hand, an LCA study shows that their LCA scope was subject to the exclusion of the emissions from transportation and distribution process as those impacts were believed <2.5 % of the total GHG impacts of the study (Strazza et al., 2010). Despite this, it is still observed that there is a lack of reliable models derived from actual emission data from maritime transportation.

LCA studies on marine fuels tend to primarily focus on evaluating the environmental performance of alternative fuels in comparison to conventional fossil fuels, as highlighted in Table 1. In particular, a number of studies have been conducted to evaluate the environmental impacts of using LNG as a marine fuel, with varying results depending on the assumptions and scenarios used. (Lindstad and Rialland, 2020; Spoof-Tuomi and Niemi, 2020) compared the emission levels of LNG in shipping with conventional MDO. (Pavlenko et al., 2020) also argued that the increased use of LNG as marine fuel would not contribute to emissions reductions and could potentially exacerbate the climate impacts of shipping if a 20-year global warming potential (GWP) was used as the impact assessment standard. Similar arguments were raised through some follow-up research. (Manouchehrinia et al., 2020) found that while natural gas (NG) engines with diesel cycles reduced GHG emissions by 2 % compared to low sulphur petroleum diesel engines, other types of NG engines, such as lean-burn Otto

Table 1
Previous LCA studies on marine fuels.

Author(s) and publication date	Type of fuels	GHG emission Scope	Methodological choice	Geographical coverage for production	Maritime transportation (international)
(Strazza et al., 2010)	Methanol, Bio-methanol, LNG, Hydrogen in Solid Oxide Fuel Cells (SOFC)	CO_2, CH_4, and N_2O	(no indication)	• Methanol: Global average • LNG: Norwegian natural gas • Hydrogen: average European plants	(no indication*) *Excluded from the analysis (since fuel storage and bunkering phases, involving tank container and fuel distribution via pipeline, do not contribute for >2.5 %)
(Bengtsson et al., 2011)	HFO, MGO, LNG, GTL (gas-to-liquid)	CO_2, CH_4, and N_2O	Consequential	• Crude oil (HFO, MGO): European • LNG, GTL: North Sea	• HFO, MGO: ELCD database • LNG: 147 K LNG carrier from Qatar to Rotterdam • GTL: Product tanker from Qatar to Gothenburg
(Bengtsson et al., 2012)	HFO, MGO, Rapeseed methyl ester (RME), Synthetic bio-diesel (BTL), LNG, Bio-LNG	CO_2, CH_4, and N_2O	Consequential	• Crude oil (HFO, MGO), BTL: European • LNG: North Sea • RME, Bio-LNG: Sweden	• LNG: LNG carrier
(Brynolf et al., 2014)	HFO, LNG, NG based Methanol, bio-LNG, Bio-methanol	CO_2, CH_4, and N_2O	Consequential	• HFO: European • LNG & Methanol: natural gas from Norway and North African countries • Bio-LNG & Bio-methanol: Sweden	• LNG: LNG carrier from North sea/Norway to Gothenburg • Methanol: tanker from North Africa to Gothenburg via Rotterdam
(Gilbert et al., 2018)	HFO, MDO, LNG, Hydrogen, Methanol, Bio-LNG, Bio-diesel, Straight vegetable oil (SVO)	CO_2, CH_4, and N_2O	Attributional	• All fuels: European	• SVO: soybean grain from transported by ship from Argentina to Europe
(El-Houjeiri et al., 2019)	HFO, MGO, LNG	CO_2, CH_4, and N_2O	Attributional	• Crude oil (HFO and MGO): Saudi, North sea • LNG: Australia, Qatar, USA	• LNG:138 K LNG • HFO: tanker from East Asia, Norway, UK to US, Japan refineries
(Hwang et al., 2019)	MGO, LNG	CO_2, CH_4, and N_2O	Attributional (GaBi)	• LNG: Qatar, USA • Crude oil(MGO): Saudi Arabia, USA	• 147 K LNG Carrier from Qatar/USA to Korea • 57 K Tanker from Saudi Arabia/ USA to Korea
(Thinkstep, 2019)	HFO, LSFO, MGO, LNG	CO_2, CH_4, and N_2O	Attributional (GaBi)	• All fuels: Global	• Data from GaBi model
(Sharafian et al., 2019)	HFO, LNG	CO_2, CH_4, and N_2O	(no indication) (GREET)	• All fuels: Global (based on North America)	• Data from GREET model
(Winebrake et al., 2019)	MDO, Methanol, LNG	CO_2, CH_4, and N_2O	(no indication) (GREET)	• All fuels: USA • Methanol produced outside of North America	• Methanol: ocean tanker when methanol is produced outside of North America
(Lindstad and Rialland, 2020)	HFO, LSFO, MGO, LNG	CO_2, CH_4, and N_2O	(no indication)	• Literature review	(no indication)
(Perčić et al., 2020)	Methanol, Dimethyl ether, LNG, Hydrogen, Biodiesel, Electricity	CO_2, CH_4, and N_2O	(no indication) (GREET)	• USA: data from GREET	• Diesel: Tanker from Middle East • Methanol: Tanker form Egypt • LNG: LNG Carrier from Qatar
(Spoof-Tuomi and Niemi, 2020)	MDO, LNG, Bio-LNG	CO_2, CH_4, and N_2O	(no indication)	• MDO: - • LNG: extracted from North Sea	• MDO: dedicated tankers • LNG: pipeline to the central hub in Finland
(Seithe et al., 2020)	HFO, LNG	CO_2, CH_4, and N_2O	(no indication)	• HFO: Russia and North Sea • LNG: North sea and onshore Algeria	• HFO: pipeline to Rotterdam • LNG: Pipeline and LNG carrier
(Pavlenko et al., 2020)	HFO, LSFO, MGO, LNG	CO_2, CH_4, and N_2O	(no indication) (GREET)	• LNG: USA • Petroleum (HFO, LSFO, MGO): USA and Canada	• Average international transport value from literature review
(Manouchehrinia et al., 2020)	LNG, MGO	CO_2, CH_4, and N_2O	(no indication)	• LNG: Canada • MGO: data from GHGenius 5	• LNG: pipeline • MGO: Data from GHGenius
(Jang et al., 2021)	HFO, LNG	CO_2, CH_4, and N_2O	(no indication)	• HFO, LNG: Literature review	(no indication)
(Comer and Osipova, 2021)	HFO, LSFO, MGO, LNG	CO_2, CH_4, N_2O and Black carbon	(no indication) (GREET)	• LNG: USA • Petroleum (HFO, LSFO, MGO): USA and Canada	• Average international transport value from literature review
(Malmgren et al., 2021)	Bio-methanol, Fossil methanol, Electro-methanol (eMeOH), MGO	CO_2, CH_4, and N_2O	Attributional	• All fuels except MGO: North European • MGO: Global average	(no indication)
(Lindstad et al., 2021)	HFO, MGO, LNG, LPG, Methanol Ammonia, Hydrogen	CO_2, CH_4, and N_2O	(no indication)	(no indication)	(no indication)
(Fernández-Ríos et al., 2022)	Hydrogen	CO_2, CH_4, and N_2O	(no indication)	(no indication)	(no indication)
(Chen and Lam, 2022)	Diesel oil, Hydrogen	CO_2, CH_4, and N_2O	(no indication)	• Diesel: European(ELCD database) • Hydrogen: Literature review	• Diesel oil: ELCD and Ecoinvent 3.6 database
(Seddiek and Ammar, 2023)	HFO, Ammonia	CO_2, CH_4, and N_2O	(no indication)	(no indication)	(no indication)

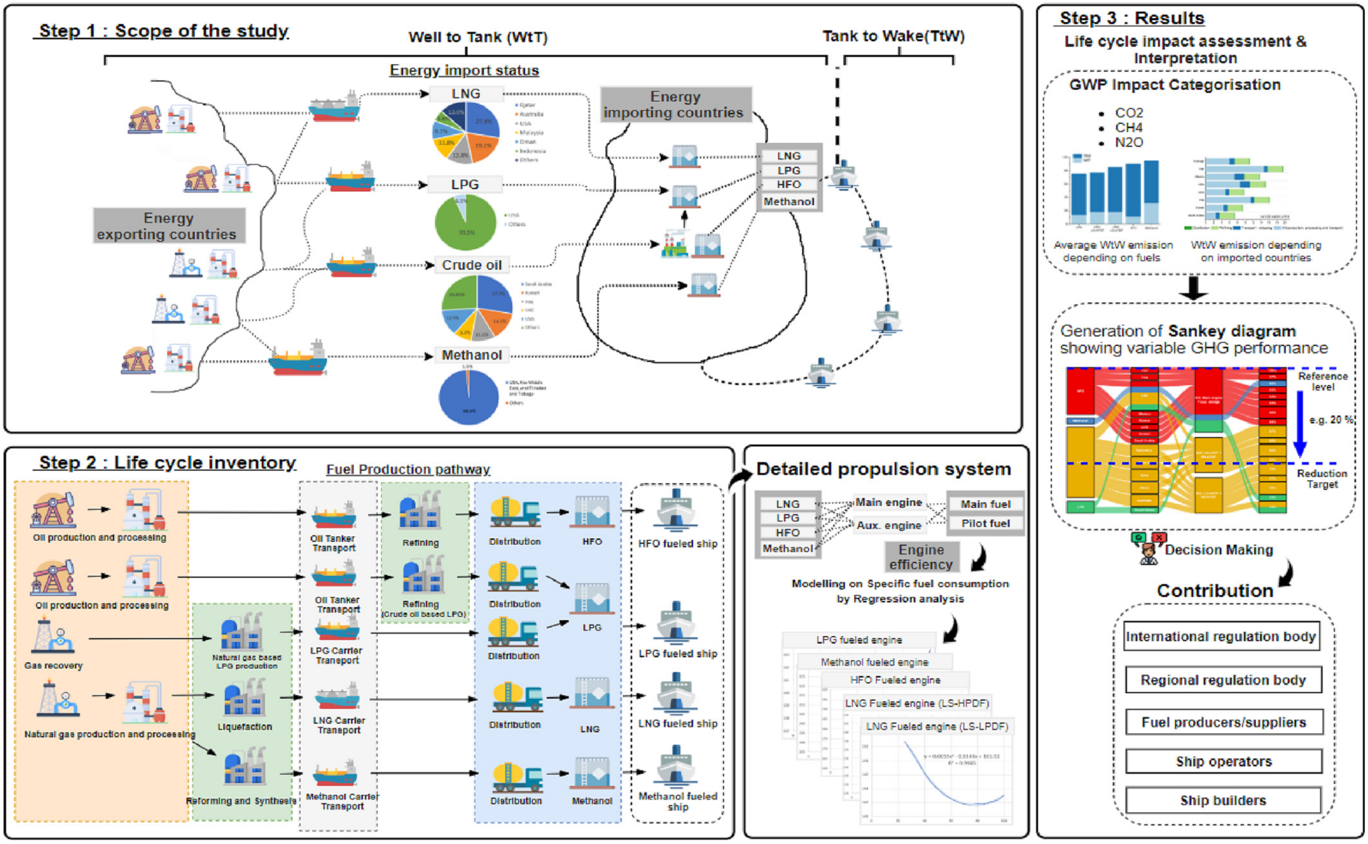


Fig. 3. Life cycle assessment framework and methodology flowchart.

cycle engines, resulted in 4 % greater GHG emissions from a life cycle perspective. This study raises questions about WtT emissions and does not support the widespread adoption of NG fuel. (Hwang et al., 2019) also conducted a comparative analysis of WtW emissions from a ship using LNG and MGO. These studies all found that LNG is not always a cleaner option than conventional marine diesel oil (MDO) and it may not contribute to reducing GHG emissions. However, these studies appear to fall short of the objective of establishing the present level of life cycle GHG emissions from marine fuels for the purpose of setting targets.

2.1. Research gaps

Numerous studies have aimed to compare the life cycle GHG emissions of conventional fossil fuels with alternative fuels. However, despite these efforts, the lack of clear guidance or practice for establishing a baseline of life cycle GHG emission values, particularly in countries that rely on energy imports, still remains. This research gap emphasizes the pressing need for default GHG emission values with a unified LCA approach and identification of impact to importing countries due to regional or geographic differences values for enhancing the LCA frameworks of national and regional regulations. This study aims to fill the identified research gaps by providing a comprehensive understanding of the present level of life cycle GHG emissions of conventional marine fuels produced and supplied in energy importing counties. The previous LCA studies, as shown in Table 1, have been inadequate in providing a clear answer to the raised research question.

3. Material and method

The method was so proposed to compare the well-to-wake GHG emission impacts of HFO, LPG, LNG and methanol as a marine fuel bunkered in energy importing countries that the research findings could contribute to developing robust default WtW emission value for conventional marine fuels. In this research, South Korea was selected as the case region for the reason that it has great low primary energy production and heavily relies on energy imports from other countries. Fig. 3 shows the methodology applied in this study. Life cycle assessment (LCA) is used to evaluate the well-to-wake environmental impact of fuel products and their process activities.

3.1. Scope of the study

Section 3.1 clarifies the scope of this study. First, the ship fuels to be considered in this study are reviewed, and the methodology to ensure that the study is properly conducted is specified.

Table 2
Overview of key properties of different fuels (Ampah et al., 2021; DNV, 2019a).

	HFO	LNG	LPG (propane/butane)	Methanol
Carrying temperature (°C)	Ambient	−162	−42	Ambient
Flash point (°C)	>61	−188	−104	11–12
Auto ignition temperature (°C)	230	537	410–580 (depending on the composition)	470
Flammability limits (volume % in air)	0.6–7.5	5–15	1.8–10.1	6.7–36
Toxicity	Not toxic	Not toxic	Not toxic	Low acute toxicity (dangerous for humans)
Energy density (MJ/L)	35.2	21.2	26.7	14.9

Table 3
The status of development for safety regulations on alternative fuels.

	Type of Fuel	Safety regulations	Effective date
1	LNG	MSC.391(95) International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code) - Part A-1	January 2017
2	Methanol	MSC.1/Circ.1621: Interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel	December 2020
3	LPG	Interim guidelines for the safety of ships using LPG fuels	June 2023 (Approval at MSC 107)
4	–	MSC.1/Circ.1647: Interim guidelines for the safety of ships using fuel cell power installations	June 2022

3.1.1. Selected marine fuels: HFO, LNG, LPG and methanol

Four fuels, namely heavy fuel oil (HFO), liquefied natural gas (LNG), liquefied petroleum gas (LPG), and methanol, have been identified as suitable candidates for the development of reliable default GHG emission values due to their high technical readiness levels (TRLs), technical maturity, and robust safety standards, in contrast to other fuels with lower TRLs (Fun-sang Cepeda et al., 2019; Kouzelis et al., 2022; Ortega et al., 2021; Turnau et al., 2020). Among conventional fuels, this study solely focuses on HFO, as it remains the dominant fuel in the shipping sector, accounting for 79 % of total fuel consumption (IMO, 2020).

Safety regulations for alternative fuels tend to be developed and applied after technical maturity and feasibility of technology on board ships are secured. Over the past decade, in order to minimize the risk to the ship and its crew due to the nature of the fuels involved (see Table 2). In addition, IMO has developed safety regulations for LNG, LPG and methanol for their application to merchant vessels as shown in Table 3.

(a) Heavy fuel oil (HFO)

Since the 1960s, HFO has been used primarily on board ships and about 99 % of the world fleets use conventional fuel by internal combustion engines as shown in Fig. 1. Since it is a residual fuel from the distillation and cracking of petroleum, it contains various compounds such as sulphur and nitrogen that create more pollutants than other fuels (Carvalho et al., 2023). SO_x and NO_x emissions from international shipping were estimated 10–15 % of the total global anthropogenic emissions and it accounts for about 3 % of global CO_2 emissions (Smith et al., 2015). These air pollutants from ships can cause serious health and environmental harm. In response, IMO has implemented stringent regulations related to sulphur content in the fuel oil and NO_x emission from engines.

(b) Liquefied natural gas (LNG)

LNG-fueled ships are gradually increasing to reduce GHG. LNG is mainly composed of methane (CH_4) which becomes liquid at a temperature of −160 °C at atmospheric pressure (Holzer et al., 2017). In comparison to conventional fuels such as HFO, natural gas is known as a cleaner fuel to reduce SO_x, NO_x, and Particulate Matter (PM) (Bilgili, 2021). As a result, the 4th IMO GHG Study shows a 150 % increase in methane emissions from ships between 2012 and 2018 due to the increased number of LNG-fueled vessels. However, LNG has been challenged due to the emissions of unburned methane at the combustion process from LNG-fueled engines (Mavrelos and Theotokatos, 2018).

(c) Liquefied petroleum gas (LPG)

More than 71 ships using LPG fuel have been built or converted by 2022 (WLPGA, 2021). LPG is any mixture of propane (C_3H_8) and butane (C_4H_{10}) in liquid form. Unlike LNG, it can be easily handled at ambient temperature with a pressure of 10–20 bar (WLPGA, 2017). Using LPG as a fuel can reduce GHG emissions and other pollutants to the atmosphere compared to conventional fuels. It can eliminate SO_x emissions and reduces GHG by approximately 17 % compared to HFO (Brinks and Chryssakis, 2017). For a two-stroke diesel engine, NO_x emissions can be expected to be reduced by 10–20 % compared to HFO (Pham et al., 2021). LPG could serve as a transition fuel to ammonia since the energy conversion system fitted onboard using LPG may be compatible with system for ammonia through its minor modification (DNV, 2019b).

(d) Methanol

54 methanol-fueled ships are already in operation or on order according to DNV's online platform (DNV, 2022). Methanol (CH_3OH) is a simple alcohol which is currently used to propel commercial vessels. It can just utilize existing shore infrastructures for conventional fuel with small and minor modifications (de Fournas and Wei, 2022). From an infrastructure standpoint, methanol is already available worldwide for distribution and storage capacity (Sun and Aziz, 2021). 88 out of the largest international ports already have the methanol bunkering infrastructure in place (Martin, 2021). It is mainly produced from natural gas but can also be made from coal and various agricultural wastes. Methanol is easier to handle than LNG as it is liquid at atmospheric conditions (Thaler et al., 2022). However, it is a low flash point and toxic fuel, so it is important to handle it onboard with caution (Zhao et al., 2021).

3.1.2. Methodological choices

The WtW emissions for selected fuels consist of two parts: WtT and TtW. This study was to consider WTW analyses for ship constructions and infrastructure development for fuel production out of scope. Instead, it was focused on the cradle-to-grave assessment of marine fuels under the current infrastructure and existing ships. For comparison between fuels investigated, the functional unit (g CO_2 eq./MJ) was defined as CO_2 equivalent emission grams per MJ of produced fuel. For the evaluation of GHG emissions, three representative GHGs -CO_2, CH_4, and N_2O- were investigated. The calculation of GHG emissions is based on the standard of a one-hundred-year time horizon impact assessment (GWP100), which is widely adopted as a standard method in international policy practices. Their global warming potentials were proposed at 1, 28, and 265 times, when compared to CO_2, respectively and those potentials were adopted to calculate the total CO_2-equivalent emissions referring to the overall WtW GHG emissions in this study. Due to geopolitical reasons, all the fuels in South Korea are imported via only maritime transportation. The statistical data for 2020 was used as a mostly updated one that could provide national energy data sufficient for the evaluation. The methodological choices applied in this study are detailed in Table 4. This study employs an attributional approach to evaluate the environmental impact of fuels, which involves analyzing the resources and emissions that are directly associated with the production and utilization of the fuel.

Table 4
Summary of the methodological choices.

Methodological item	Selection
Selected fuels	HFO, LNG, LPG and methanol
Impact category	Global Warming Potential with the 100-year time frame
GHG emissions scope	CO_2, CH_4, and N_2O
Geographical coverage	From producing countries to South Korea
System boundaries	WtT part covers fuel production and its transportation to ships onboard while the TtW scope covers the emission
Functional unit	CO_2 equivalent emission grams per MJ of produced fuel (g CO_2 eq./MJ)
LCA methodology	Attributional approach (A-LCA)
Allocation method	Energy based allocation is prepared

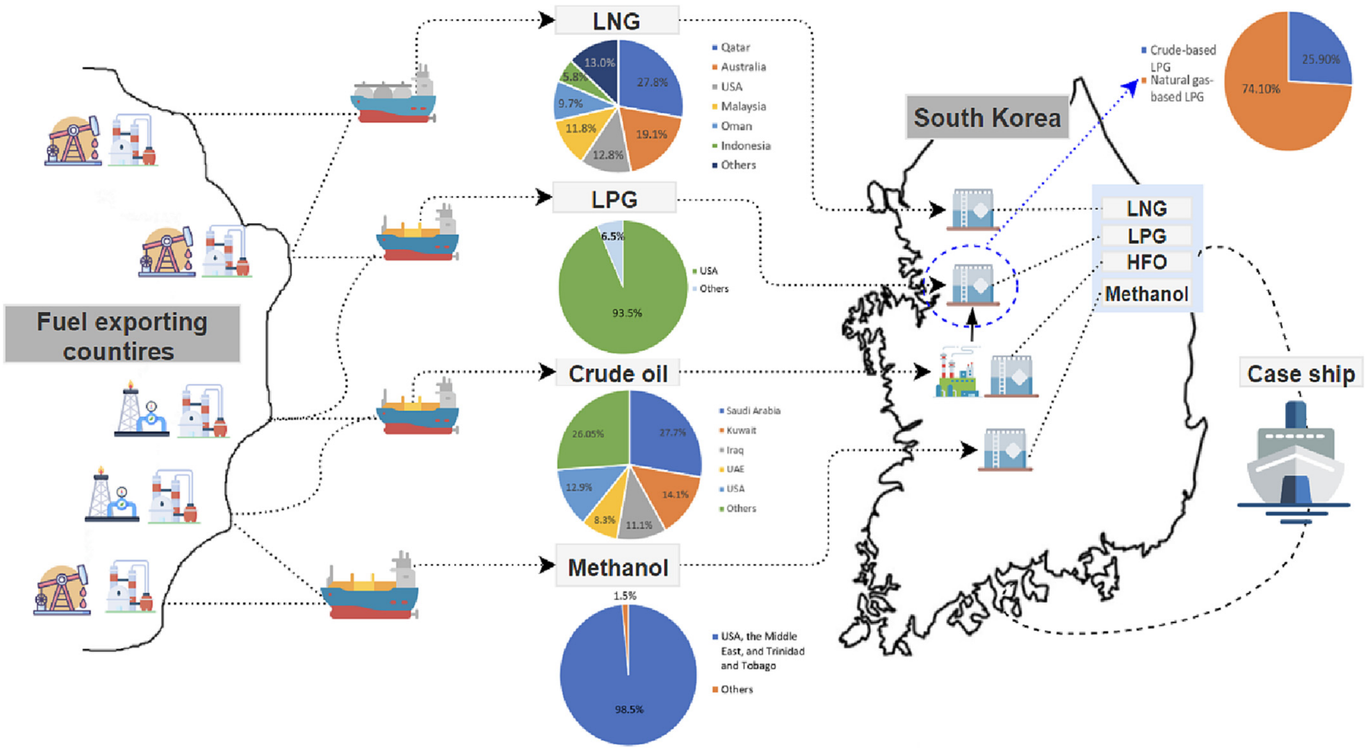


Fig. 4. Imports of Crude oil, LNG, LPG and methanol to South Korea.

3.2. Data collection and generation

In this section, relevant data is collected and safeguarded to ensure accurate and precise research within the scope defined in Section 3.1. The analysis was performed by segmenting the fuel lifecycle into two stages: the upstream stage encompassing production to storage (Well-to-Tank), and the downstream stage (Tank-to-Wake), representing the use aspect.

3.2.1. Well-to-Tank inventory analysis

Fig. 4 summarizes the pathway and their ratios of the proposed fuels from the producing countries to South Korea. LNG, LPG, Crude oil, and methanol are imported from overseas, but crude oil-based LPG is produced in domestic refineries and small amounts of natural gas are also produced in South Korea.

The WtT GHG emissions are determined by geological characteristics, transportation means, and fuel production methods (Manouchehrinia et al., 2020). The fuel production pathways for HFO, LPG, LNG and methanol were identified and modelled as shown in Fig. 5 in order to assess their WtW GHG emissions. The pathways were also categorized into four steps: Efs, Ec, Et, and Ed, as shown in Eq. (2). This was done to standardize the approach and enable comparison of the pathways. Furthermore, WtT inventory was also compiled, considering the specifics of energy producing/exporting countries. The more detailed data used in the analysis are summarized in the supplementary material. In this study, the weighted average WtT GHG emissions associated with imported energy sources or fuels were estimated using the following equation.

•

$$\text{Average WtT GHG emission} = \frac{\Sigma_i^{n\ countries}(P_i \times \mathrm{WtT}_i\,)}{\Sigma_i^{n\ countries} P_i} \qquad (1)$$

•

$$\mathrm{WtT_i} = \mathrm{Efs} + \mathrm{Ec} + \mathrm{Et} + \mathrm{Ed} \qquad (2)$$

where; P_i: the percentage (%) of a specific energy source or fuel imported to South Korea from a particular country, $\mathrm{WtT_i}$: WtT emission value ($gCO_2eq.$/MJ) of fuels imported from a particular country, based on production pathway in Fig. 5, Efs: emissions associated with feedstock extraction, recovery, and transport, excluding international maritime transportation, Ec: emissions resulting from the conversion of the feedstock to the final fuel product, as well as emissions associated with the transportation and storage of the finished fuel, excluding international maritime transportation, Et: emissions specifically linked to international maritime transportation for the feedstock or the finished fuel, Ed: emissions associated with the distribution phase, encompassing local delivery, retail storage, and bunkering.

(a) Heavy fuel oil (HFO)

South Korea imports crude oil from overseas via maritime transportation and HFO is produced from this oil production through domestic refineries. The data of crude oil imported were collected based on the eight major crude oil producing countries accounting for approximately 84.2 % of the total crude oil imports as listed: Saudi Arabia, Kuwait, Iraq, USA, UAE, Mexico, Iran and Russia (Korea Petroleum Association, 2022).

Case-specific emissions data for crude oil production across different countries was obtained from the “Oil Production Greenhouse Gas Emissions Estimator” (OPGEE), which is currently considered the most reliable public data (El-Houjeiri et al., 2019; Masnadi et al., 2018; Thinkstep, 2019). It provides GHG emission data for some specific countries corresponding to production processes of both conventional and alternative fuels.

However, in relation to crude oil imports, OPGEE model was adopted using identical default emission values for crude oil transportation through ocean tanker with 250,000 tons for carriage and 8000 miles for operation. In this study, the actual ship operation data from a Korean shipping company was used to estimate the emissions by maritime transportation. Table 5 shows the details obtained from operational data (namely Abstract LOG) that includes the information of ship voyages such as calling in and out ports, navigation distance, average speed, and fuel consumption (MOL, 2022). The GHG emissions of crude oil, LNG and LPG during the maritime transportation were estimated with the following equation. The determination of emission factors(EF_{GHG}) is achieved through the integration of per unit emissions of various greenhouse gases in relation to fuel consumption, as well as the consideration of their corresponding global warming potentials.

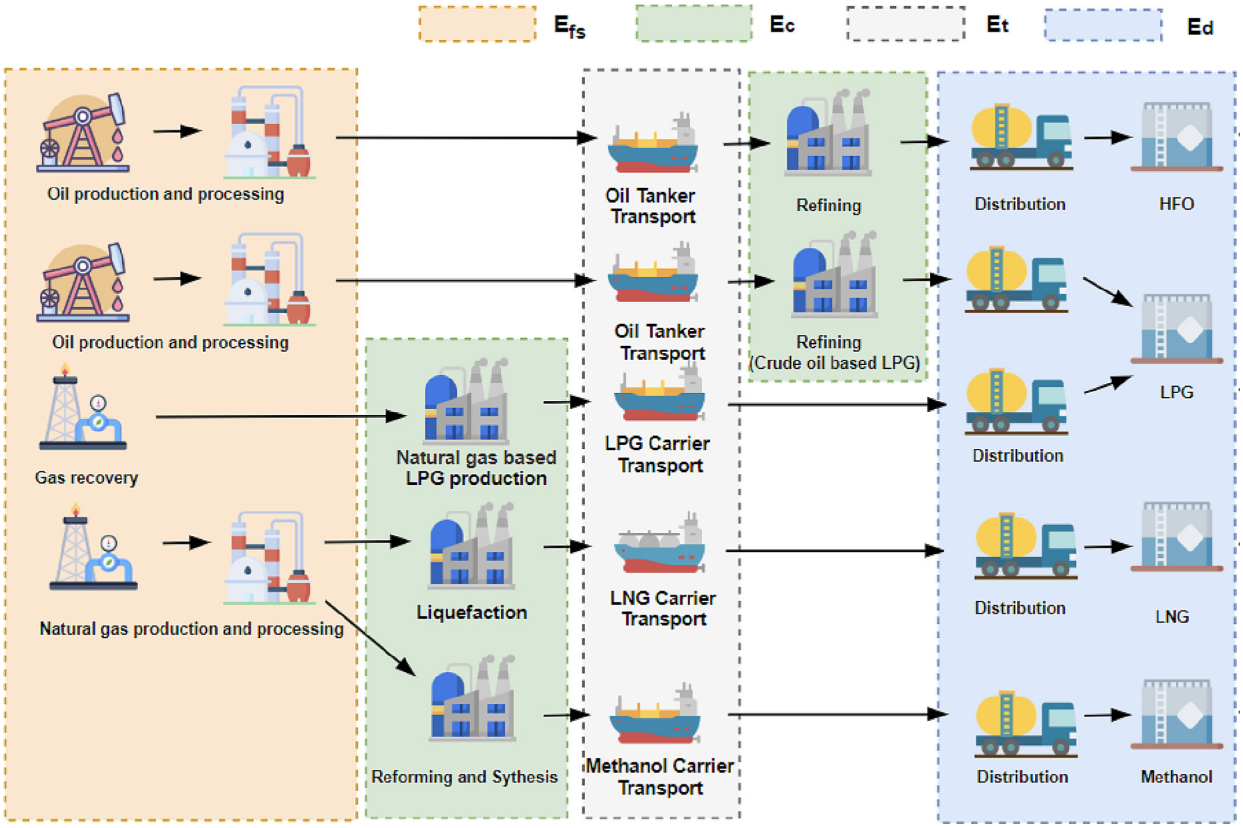


Fig. 5. Production pathway modelling for HFO, LNG, LPG, and methanol in South Korea.

-
$$Et = \frac{\Sigma_i^{n\ fuel}\Sigma_j^{m\ engine} M_{i,j} \times EF_{GHG}}{M_{cargo} \text{ x } LHV} \tag{3}$$

-
$$EF_{GHG} = Cf_{CO2} + Cf_{CH4} \text{ x } GWP_{CH4} + Cf_{N2O} \text{ x } GWP_{N2O} \tag{4}$$

where; E_t: emissions during the maritime transportation (CO_2 eq./MJ), $M_{i,j}$: consumption of the specific fuel i oxidized in consumer j (t fuel) of ships, M_{cargo}: Mass of the specific cargo carried (t cargo), LHV: Lower heating value of $fuel_i$, EF_{GHG}: GHG emission factor (t/t fuel) corresponding to each fuel, Cf_{CO2}: the conversion factor between selected fuel consumption and CO_2 emission (t CO_2/t fuel), Cf_{CH4}: the methane emission factor (t CH_4/t fuel), Cf_{N2O}: the nitrous oxide emission factor (t N_2O/t fuel), GWP_{CH4}: Global warming potential for CH_4, equals to 28 for 100-year time horizon, GWP_{N2O}: Global warming potential for N_2O, equals to 265 for 100-year time horizon.

Table 5
Ship specifications for maritime transportation.

Type of cargo	Maritime transportation			
	Applied propulsion system	Main fuel types	Cargo capacity (m3)	Geographical coverage (Imported countries)
Crude oil	LSD	HFO	300 K	Saudi Arabia, Kuwait, Iraq, UAE, USA, Mexico and Iran
LNG	Steam turbine (Main boiler)	HFO, LNG	125 K	Malaysia Indonesia Australia
			135 K	Qatar Oman
	LS-HPDF		174 K	USA
LPG	LSD	HFO	82 K	USA
Methanol	LSD	HFO	55 K	USA

Note: Low-speed diesel cycle engines (LSD), Low-speed high-pressure dual-fuel engines (LS-HPDF), Low-speed low-pressure dual-fuel engines (LS-LPDF), Medium-speed low-pressure dual-fuel engines (MS-LPDF).

The data of emissions incurred in a refinery to distillate from crude oil to HFO was from published data which adopted process-level allocation method to calculate the refining energy use of individual petroleum products (Choi et al., 2020; Jang and Song, 2015).

(b) LNG

Despite a small domestic production, most of the LNG consumed in South Korea is imported from several countries. Given this, this paper assumes all LNG to be produced overseas and imported to South Korea with the following ratios: Qatar (27 %), Australia (19 %), USA (14 %), Malaysia (12 %), Oman (9 %), Indonesia (6 %), Other (13 %) (KOGAS, 2020).

The data pertaining to the emissions and energy consumptions (such as electricity, diesel oil and natural gas) during the production, liquefaction, and transportation of natural gas were obtained from GaBi database and the research products of the Natural Gas & bio Vehicle Association (NGVA) (Schuller et al., 2019; Schuller et al., 2017). Data on fuel consumption and its emissions for LNG carrier transport were calculated during the actual ship's operation for approximately 100 voyages, based on the specifications in Table 5. The methane loss data for LNG terminal operations and LNG bunkering were included in distribution phase(Ed). These data were taken from the NGVA study and GaBi database (Schuller et al., 2019; Schuller et al., 2017). It should be noted that unlike other fuels, methane loss in the distribution phase only occurs during LNG terminal and bunkering operations.

(c) LPG

South Korean LPG mainly consists of crude oil-based LPG (25.9 %) made from domestic refineries and natural gas-based LPG (74.1 %)

imported from overseas (KOSIS, 2022). The natural gas-based LPG imported from the USA accounts for about 93 % while the rest is from other countries (Korea Petroleum Association, 2022). To simplify the analysis in this study, all imported LPG was assumed to be made from natural gas liquids (NGLs) produced in the USA.

For the inventory analysis of crude oil-based LPG, the emission data from domestic refineries, including liquefaction, were mainly obtained from past publication (Choi et al., 2020). The actual operation data from the Korean shipping company was used to estimate the emissions by international transportation. The average WtT GHG emissions values of LPG were obtained as a weighted average based on the amount of domestic LPG produced and imported in 2019.

(d) Methanol

Given the mature methanol synthesis pathway, which accounts for 90 % of global methanol demand, it is assumed that all methanol will be produced from natural gas. Its key process includes steam reforming of natural gas and methanol synthesis reactor (Adnan and Kibria, 2020). Approximately 98 % of methanol shipped to South Korea originated from the USA, the Middle East, and Trinidad and Tobago (ARGUS, 2023). However, due to a lack of available data, the WtT GHG emissions for methanol production in the USA specifically were adopted from the latest version of the GREET model (Wang et al., 2021). The feedstock for methanol production in the USA consists of 74.7 % natural gas from shale production and 25.3 % from conventional recovery practices. The transportation emissions data for methanol carrier was assumed based on the average emissions for a 55 K methanol carrier traveling between the USA and South Korea.

3.2.2. Tank-to-Wake inventory analysis

In the Tank-to-Wake analysis, which represents the downstream stage, a comprehensive analysis was conducted by subdividing it into case ship selection, propulsion engine, auxiliary engine, fuel consumption calculation/estimation, and GHG emissions assessment.

3.2.2.1. Selection of case ship. In order to compare TtW and WtW emissions of the selected fuels, a bulk carrier of M/V Ilshin Green Iris built in 2018 was selected. The main particulars were obtained from the Korean Register while ship's operational data corresponding to six months were collected from ILSHIN SHIPPING Co., Ltd. Table 6 summarizes general specifications and operational profiles of the selected ship.

The same specifications as MCR (7250 kW × 88.7 RPM) and NCR (NCR: 5597 kW × 81.4 RPM) were used in selecting the engine type using HFO, LPG, LNG, and methanol.

3.2.2.2. Calculation of TtW GHG emissions and average GHG intensity. In order to estimate the annual GHG emissions from onboard ships, fuel consumption and GHG emission factors should be sought. The fuel consumptions are multiplied by the TtW emission factors with the following equation, which has been applied to IMO instruments: IMO DCS, CII and EEOI. The determination of TtW emission factors(EF_{GHG}) is achieved through the Eq. (4).

Table 6
Specifications and operational profiles of the case ship.

Specification	Details
Length × Breadth × Depth	190.63 m × 32.26 m × 17.3 m
Service speed	14 knots
Deadweight	50,655 tons
Main Engine	Low-speed high-pressure dual-fuel engines (LS-HPDF) (6G50ME-GI)
MCR/NCR	MCR: 7250 kW × 88.7 RPM NCR: 5597 kW × 81.4 RPM
LNG fuel tank	500 m^3
Cruising range	Abt. 600 miles per one voyage from Donghae port to Gwangyang port located in south Korea
Average main engine load	72.5 % of MCR

-

$$E = \Sigma_i^{n\ fuel}\Sigma_j^{m\ engine}M_{i,j} \times EF_{GHG} \tag{5}$$

The average GHG intensity of the fuel used on board ships are estimated using the following equation.

-

$$Et = \frac{E}{\Sigma_i^n M_i \times LHV_i} \tag{6}$$

where; E: Estimated annual emission amount (t), $M_{i,j}$: Consumption of the specific fuel i oxidized in consumer j (t fuel) of ships, EF_{GHG}: TtW GHG emission factors average GHG intensity of the fuel used (CO_2 eq./MJ) and LHV: Lower heating value of $fuel_i$.

3.2.2.3. Types of propulsion engines.

(a) LNG Fueled engine: low-speed high-pressure dual-fuel engines(LS-HPDF)

The MEGI engine (M-type Electronically Controlled Gas Injected engine), whose first vessel was delivered in 2016, applies the diesel cycle with non-premixed combustion. As opposed to the Otto-cycle combustion, natural gas fuel with high pressure of about 300 bar is injected into the combustion chamber together with 5 % amount of pilot fuel to ensure optimal combustion (Domić et al., 2022).

(b) LNG Fueled engine: low-speed low-pressure dual-fuel engines (LS-LPDF)

The dual fuel engine employs low-pressure gas fuel and operates on the Otto-cycle combustion process utilizing premixed fuel/air and a relatively high air-to-fuel ratio. A minimal volume of pilot fuel, comprising approximately 1 % of full load fuel consumption, is required for ignition of the premixed fuel/air. Unlike high-pressure gas injection engines, the utilization of low gas pressure, approximately 13 bar, is sufficient to attain a homogenous air/gas mixture across the full range of engine loads due to the injection of gas at the start of compression (WIN GD, 2023).

(c) LPG-fueled engine and Methanol fueled engine

The dual-fuel ME-LGI engine is a novel propulsion system that is designed to operate using low-flashpoint liquid fuels, as opposed to the gaseous fuels utilized by LNG-fueled engines. The ME-LGI engine, which employs a diesel combustion cycle, is available in various versions, each optimized for a specific low-flashpoint fuel type (MAN Energy Solutions, 2023). For example, the ME-LGIP and ME-LGIM engines are specifically engineered for operation with LPG and methanol fuels, respectively. The methanol fuel supply system employed in the ME-LGIM engine is similar in design to that of conventional heavy fuel oil (HFO) engines. The fuel is supplied at a pressure of approximately 10 bar and the injection pressure at the engine combustion cylinder is around 500–550 bar (MAN Energy Solutions, 2014). In contrast, the ME-LGIP engine utilizes LPG fuel that is supplied at a pressure of 50 bar and is further pressurized to 600–700 bar by the high-pressure hydraulic oil system. Additionally, the ME-LGIP engines have the capability to operate in gas mode with minimal usage of pilot oil, typically at 3–10 % at low loads, while the ME-LGIM engines require a minimum pilot oil percentage of 5 % when operating on methanol with not only a low cetane number but also low self-ignition quality (MAN Energy Solutions, 2021).

Based on selected propulsion engines above, the summary of emission data from propulsion engines can be found in Table 7. For all CO_2 emission

Table 7
The data for estimating annual TtW GHG emissions for main engines using LNG, LPG, HFO and methanol.

Main engine type	LNG Fueled engine		LPG Fueled engine	HFO fueled engine	Methanol engine
	Low-speed high-pressure dual-fuel engines (LS-HPDF)	Low-speed low-pressure dual-fuel engines (LS-LPDF)	Low-speed diesel cycle engines (LSD)	Low-speed diesel cycle engines (LSD)	Low-speed diesel cycle engines (LSD)
Engine Maker's Model	6G50ME-GI	6X-52DF	6G50ME-LGIP	6G50ME	6G50ME- LGIM
Average main engine load at sea and operation days	72.5 % / 250 Days				
Engine thermal efficiency (%) at 72.5 % of MCR	55.30	50.20	53.9	53.9	53.9
SFC (g/kWh) at 72.5 % of MCR (Main /pilot fuel)	126.85/3.9	141.75/1.95	137.9 / 7.85	147.24/ -	307.5/13.1
Emission factor (GHG t/t fuel) (IMO, 2018a; IMO, 2020; Pavlenko et al., 2020)					
CO_2	2.75	2.75	3.015	3.144	1.375
CH_4	0.001449	0.017083	0.00006	0.00006	0.000006
N_2O	0.000217	0.000137	0.00016	0.00016	0.000016

Lower heating value (LHV) of LNG: 49.2 MJ/kg, Lower heating value of LPG: 46.0 MJ/kg, Lower heating value of HFO: 40.2 MJ/kg, Lower heating value of methanol: 19.9 MJ/kg, Emission per unit of fuel energy (g/MJ fuel) = 1/3.6 × g/kWh engine output × efficiency engine, Emissions per mass of fuel (g/kg fuel) = g/MJ fuel × LHV fuel (MJ/kg).

factor between fuel consumption and CO_2 emission, it was taken by the 2018 EEDI Guidelines (IMO, 2018a). The emission factor for CH_4 varies by engine type. For LNG-fueled engines, the factors were chosen based on values of 2.50 g/kWh for LS-LPDF and 0.20 g/kWh for LS-HPDF (Pavlenko et al., 2020). They are weighted to represent E2 or E3 test cycles in IMO NO_x Technical Code. The other CH_4 and N_2O emission factors were from the 4th IMO GHG study. In particular, the factors for methanol were considered as 10 % of HFO (IMO, 2020). Due to the lack of data for the LPG fuel, the LPG emission factors for CH_4 and N_2O were substituted for those for methanol fuel.

3.2.2.4. Auxiliary engines selected. In this study, auxiliary engines using LPG, HFO and methanol are medium-speed diesel cycle engines (MSD) while the LNG-fueled auxiliary engine employs an Otto combustion process. Table 8 presents specific fuel consumption and emission factors for the auxiliary engine. The emission factors obtained from the 4th IMO GHG study. Table 8 presents the auxiliary engine and boiler power outputs depending on operational mode. Considering ship type, size and operational mode for selected case ship, the power output of the auxiliary engine is assumed to be 260 kW during sea operation and 680 kW during maneuvering (IMO, 2020).

3.2.2.5. Fuel consumption estimation model. Emissions from the main engine depend on the selected rated power, load factor, fuel type, engine type and year the engine was built. The main engine power and load factor will change over time as a consequence of the vessel's operating and activity details such as speed, loading conditions, weather, etc. (Smith et al., 2015). The power outputs required for ship propulsion are considered the results of operating speed trends. This can be represented as “loads” corresponding to the proportion of the overall installed maximum power output called MCR. In this study, based on ship's Abstract LOG data, average main engine load at sea was chosen as 72.5 % of MCR and its loads are converted to fuel consumption using the specific fuel consumption (SFC) for main fuel and pilot fuels. The dual fuel engines always operate on LNG, LPG and methanol as their primary fuels while the amount of pilot fuels injected changes depending on engine loads.

Table 8
The emission factors for estimating annual TtW GHG emissions from auxiliary engine.

Fuel	HFO	LNG	LPG	Methanol
Auxiliary Engine type	Medium-speed diesel cycle engines (MSD)	Medium-speed low-pressure dual-fuel engines (MS-LPDF)	Medium-speed diesel cycle engines (MSD)	Medium-speed diesel cycle engines (MSD)
SFOC (g/kWh)	195	152	160	370
Emission factors (GHG t/t fuel) (IMO, 2020)				
CO_2	3.144	2.75	3.015	1.375
CH_4	0.00006	0.036	0.000006	0.000006
N_2O	0.00025	0.000131	0.000025	0.000025

The annual fuel consumption of the main engine and auxiliary engine is calculated through the following equation.

- $$FC_{primary} = AML \times SFOC \times AD \quad (7)$$
- $$FC_{pilot} = AML \times SPOC \times AD \quad (8)$$
- $$FC_{aux} = AML \times SFOC \times AD \quad (9)$$

where; $FC_{primary}$: Primary fuel consumption (t) for main engine, FC_{pilot}: Pilot fuel consumption(t) for main engine, FC_{aux}: Fuel consumption (t) for auxiliary engine, AML: Kilowatts (kW) at average main and auxiliary engine load, SFOC: Specific fuel consumption (g/kWh) for primary fuel at AML, SPOC: Specific fuel consumption (g/kWh) for pilot fuel at AML, AD: Average days at sea per year.

To compare the performance of the GHG emission equivalently from engines using selected fuels, specific fuel oil consumption data (g/kWh) were collected from the engine manufacturer's engine selection software (MAN CEAS Engine Calculations and WinGD General Technical Data). The changes of SFOC and SPOC (g/kWh) were estimated as a function of engine load over the whole range. The study utilized regression analysis with R-squared values (R^2) to evaluate the fit of the model developed from the data provided by the engine manufacturer. Based on this analysis, it was determined that a cubic function was the most suitable mathematical model to describe the performance of methanol engines, whereas quadratic functions were found to be more appropriate for other types of engines. Table 7 also contains the specific fuel consumption values for each engine type at an average main engine load of 72.5 % of the maximum continuous rating (MCR). It is noteworthy to mention that these formulas enable us to predict fuel consumption based on the engine loads that are being used.

For LNG Fueled engine (LS-HPDF),

- $$SFOC\ (y) = 0.0045x^2 - 0.559x + 146.51\ \left(R^2 = 0.9566\right) \quad (10)$$
- $$SPOC\ (y) = 0.0019x^2 - 0.3024x + 15.367\ \left(R^2 = 0.9414\right) \quad (11)$$

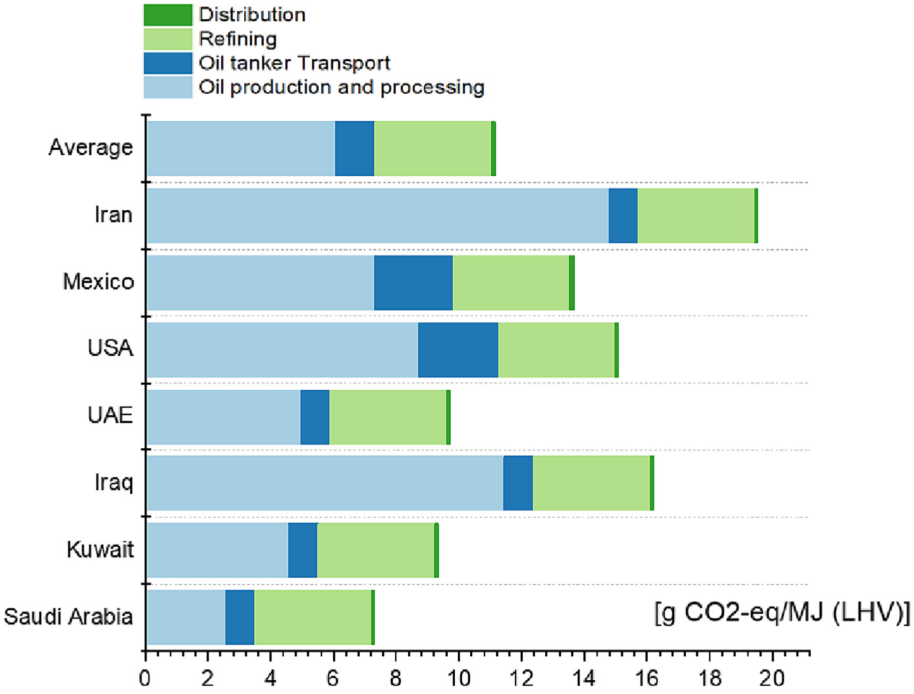


Fig. 6. WtT GHG emissions for HFO depending on imported countries.

For LNG Fueled engine (LS-LPDF),

- $$\mathrm{SFOC}\ (y) = 0.0033x^2 - 0.5148x + 161.61\ (R^2 = 0.9965) \quad (12)$$

- $$\mathrm{SPOC}\ (y) = 0.0004x^2 - 0.0807x + 5.5128\ (R^2 = 0.9908) \quad (13)$$

For LPG Fueled engine,

- $$\mathrm{SFOC}\ (y) = 0.0022x^2 - 0.2491x + 145.19\ (R^2 = 0.8209) \quad (14)$$

- $$\mathrm{SPOC}\ (y) = 0.0037x^2 - 0.5995x + 30.602\ (R^2 = 0.9383) \quad (15)$$

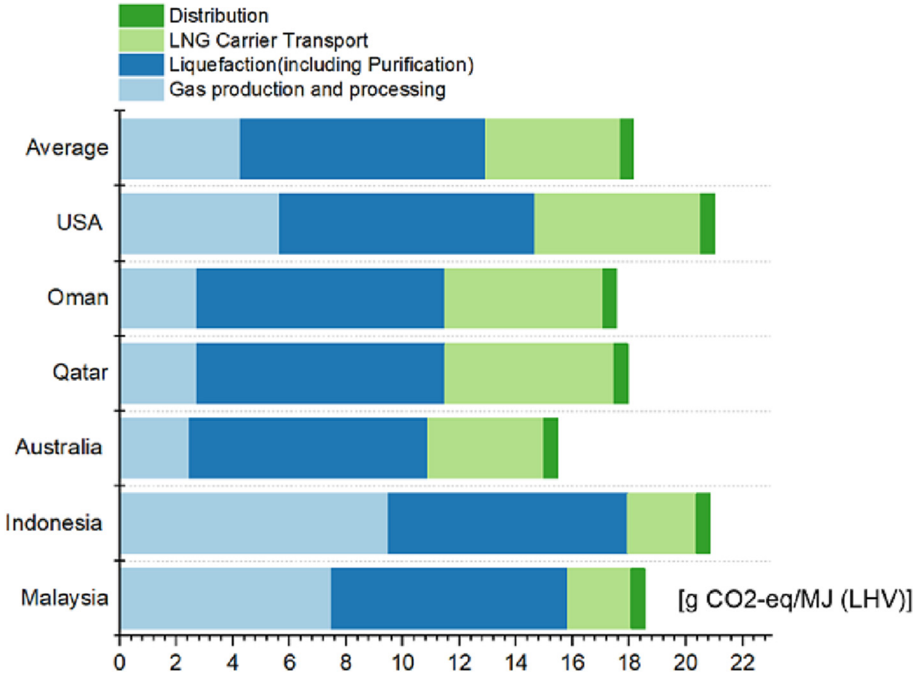


Fig. 7. WtT GHG emissions for LNG depending on imported countries.

For HFO fueled engine,

•

$$\mathrm{SFOC}\ (y) = 0.0065x^2 - 0.9238x + 198.72\ (R^2 = 0.9674) \tag{16}$$

For Methanol fueled engine,

•

$$\mathrm{SFOC}\ (y) = 0.0002x^3 - 0.033x2 + 1.8279x + 273.18(R^2 = 0.9933) \tag{17}$$

•

$$\mathrm{SPOC}\ (y) = -0.0001x^3 + 0.0282x^2 - 2.0363x + 63.508(R^2 = 0.984) \tag{18}$$

3.2.3. Impact analysis on maritime transportation

In addition to the aforementioned data collection and generation methods, this analysis was proposed to investigate the impact of geographical differences, as a key parametric variable, specifically transportation distances that reflect regional characteristics on the lifecycle emission levels. In this regard, the analysis was conducted in a way to compare three distinct functional units within the context of LNG transportation, depending on the import region. It utilized the actual data of the actual cargo (LNG) carried, voyage distances, and fuel consumption of LNG carriers operating between South Korea and different importing countries. Key findings are presented in Section 4.4.

•

$$E_c = \frac{\Sigma_i^{n\ fuel}\Sigma_j^{m\ engine} M_{i,j} \times EF_{GHG}}{M_{cargo}} \tag{19}$$

•

$$E_d = \frac{\Sigma_i^{n\ fuel}\Sigma_j^{m\ engine} M_{i,j} \times EF_{GHG}}{D} \tag{20}$$

•

$$E_{tw} = \frac{\Sigma_i^{n\ fuel}\Sigma_j^{m\ engine} M_{i,j} \times EF_{GHG}}{M_{cargo}\ x\ D} \tag{21}$$

where;

E_c: emissions per LNG ton carried (tCO_2 eq./ton), E_d: emissions per voyage distance (tCO_2 eq./mile), E_{tw}: emissions per transport work (voyage distance multiplied by the ton of LNG carried) (tCO_2 eq./ mile ▫ ton), D: Total voyage distances, For further details and calculations, please refer to Eqs. (3) and (4).

4. Results

Section 4 presents the findings of the study, with a specific focus on the analysis of the WtT GHG emissions of selected fuels in Section 4.1, the TtW GHG emissions from the main and auxiliary engines in Section 4.2, and the WtW GHG emissions, including a comparative assessment, in Section 4.3. The graphical representation of the results is presented in the main text, while the numerical values are provided in the supplementary material for reference.

4.1. Comparison of WtT GHG emissions from fuels

Fig. 6 indicates the results of WtT GHG emissions for HFO from seven imported countries. The identical trends were found that emissions for crude oil production and refining process account for a large proportion of the total WtT emissions whereas the transport emission by shipping and the emissions originated from distribution are relatively estimated to be smaller. During crude oil production, Iraq's case has about three times more emissions when compared to Saudi Arabia. In the meantime, with regard to transport emissions between seven countries, the minimum emission is 0.91 g CO_2 eq./MJ for Saudi Arabia and the maximum is 2.5 g CO_2 eq./MJ for USA while average value is 1.3 g CO_2 eq./MJ. A key finding through those figures is that it does not have significant impact on total emissions for HFO produced in South Korea. Unlike LNG and LPG, the reason for the relatively low transportation emissions by oil tanker is due to the very high transportation efficiency with large cargo capacity as this study assumed that all crude oils are transported by 300 K VLCC.

Table 9
Percentage of share and efficiency of various liquefaction technologies (Choi and Song, 2014).

	Technology share (%)	Efficiency (%)
C3MR	67.72	92.9
Cascade	14.83	91.2
SMR	1.72	91.6
DMR	3.93	92.7
AP-X	11.79	90.4–92.9

Fig. 7 shows WtT GHG emissions for LNG depending on imported countries. Although the emissions stemming from liquefaction process contribute the most to the total WtT GHG emissions, their difference is not considerable. It can be inferred that main reason that the efficiency of liquefaction is analogous across the technologies applied in each country with the range from 90.4 % to 92.9 %, as indicated in Table 9 (Choi and Song, 2014).

On the other hand, transportation emissions by LNG carriers have a wide range of emissions from 2.26 g CO_2 eq./MJ to 5.97 g CO_2 eq./MJ. Notably, Indonesia and Malaysia demonstrate comparatively lower emissions, with values of 2.26 g CO2 eq./MJ and 2.43 g CO2 eq./MJ, respectively. In contrast, Australia's transportation emissions amount to 4.11 g CO2 eq./MJ. It is intriguing to observe that, despite employing the same conventional steam turbine system and cargo capacity for transporting LNG, Australia's emissions differ from those of the other two countries. The further analysis on this difference was performed in section 4.4.

As depicted in Fig. 8, the life cycle GHG emissions for natural gas-based LPG are slightly greater than one from LPG made from crude oil. This result suggests that the feedstock nature of marine fuels is one of crucial elements to determine the level of GWP impact although they are fossil-based fuels.

For methanol, the WtT emissions are determined to be approximately 20.72 g CO_2 eq./MJ, as shown in Fig. 9. These values are derived from the utilization of the GREET model developed at Argonne National Laboratory, combined with transportation emissions data for a 55 K methanol carrier.

Among all fuels, the downstream GHG emission from HFO is the least whereas methanol is considered the most. This disparity can be attributed to the fact that methanol production is derived from fossil-based natural gas, and the energy required for the conversion of natural gas into methanol results in additional GHG emissions. However, it is important to note that the WtT emissions of HFO show the highest variability among all fuels as shown in Fig. 6 and Table S6 in the supplementary material.

4.2. Comparison of TtW GHG emissions

Fig. 10 compares estimates of the annual TtW emissions from ships using HFO, LNG, LPG and methanol fuels when using their main and auxiliary engines. The HFO-fueled ship was the greatest GHG emitter while using LNG with LS-HPDF was the lowest. Emissions from ships using these engines are approximately 17,689 t, 12,463 t (LS-HPDF),15,806 t (LS-LPDF), 13,651 t and 15,348 t respectively. Overall, compared to emissions from main engine, one from auxiliary engine has ranges of 5.2 to 7.3 % of total TtW GHG emissions.

Fig. 11 also illustrates average GHG intensity of the energy used on board ships for a given year when all emissions from ships are considered

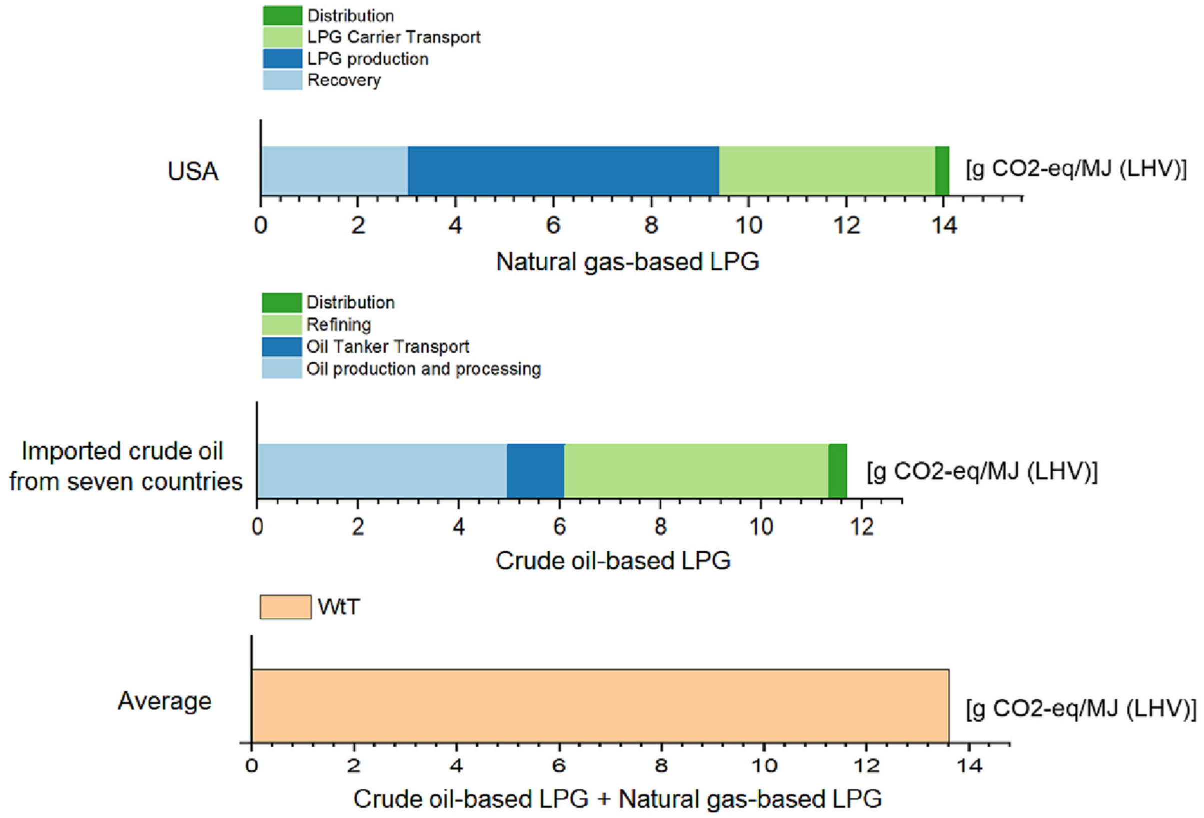


Fig. 8. WtT GHG emissions for crude oil-based LPG and natural gas-based LPG.

only from main and auxiliary engines. The trend of GHG intensity between fuels is analogous to that of annual GHG emissions indicated in Fig. 10. As a policy measure, the IMO is considering the establishment of a GHG Fuel Standard (GFS), which would require ships to use fuels or other energy sources with a WtW GHG intensity at or below a certain limit value over a compliance period (IMO, 2022c). This observation of the trends suggests that reducing the GHG intensity of the energy used on board ships through this measure will have a positive impact on achieving the annual GHG emission reduction levels in line with the ambitions of the IMO GHG Strategy. In addition, similar trends were observed across results that the emissions emitted from auxiliary engines using the same fuel as the main engines have no significant effect on the average total GHG intensity.

4.2.1. Comparison of GHG emissions between main fuel and pilot fuel

Table 10 indicates the result of specific fuel consumption (g/kWh) for main fuel and pilot fuel depending on engine load, using developed quadratic functions per each fuel engine. It can be seen that the amount of pilot fuel supplied for ensuring a stable ignition and combustion is non-identical depending on the combustion characteristics of applied each fuel and combustion cycles (e.g., otto or diesel) of the engines. Especially, other fueled engines except methanol engine have smaller pilot fuel consumptions over the higher load operation but methanol engine with engine loads from 40 % to 60 %. It is also inferred that depending on engine type and its fuel, there are technical challenges in designing a robust injection system that is small and fast enough to inject a small amount of pilot oil into the engine while it is enabled to be efficient high load operation.

Based on the data presented in Table 10, the calculation of their GHG emissions was performed. The results are illustrated in Fig. 12, which displays the contribution of main and pilot fuel to the total GHG emissions over the range of engine loads. In particular, the GHG emissions due to the use of pilot fuel tend to be high at low engine load while their emissions have a different degree of impact on total GHG at that engine load depending on the type of fuel or engine used. For instance, the emission emitted from LPG's pilot fuels occupies about 17 % at 10 % load, whereas for LS LPDF with otto cycle, it is 3 %. It is noteworthy that changing pilot fuels to renewable fuels like bio-fuel and synthetic fuel can also contribute to reducing GHG emissions. The extent of emissions reduction varies depending on the fuel, with potential reductions ranging from approximately 1 % for LNG LS-LPDF to up to 9 % for methanol at a realistic average main engine load of 70–80 %.

4.2.2. Comparison of GHG emissions from main engines

Fig. 13 presents the GHG emissions and their trends on main engines across four selected fuels, assuming they operate for the same period of

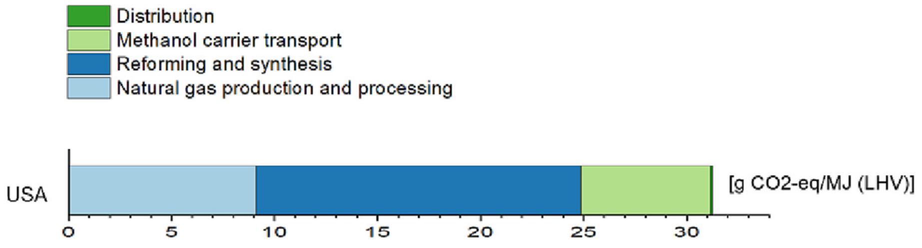


Fig. 9. WtT GHG emissions for methanol.

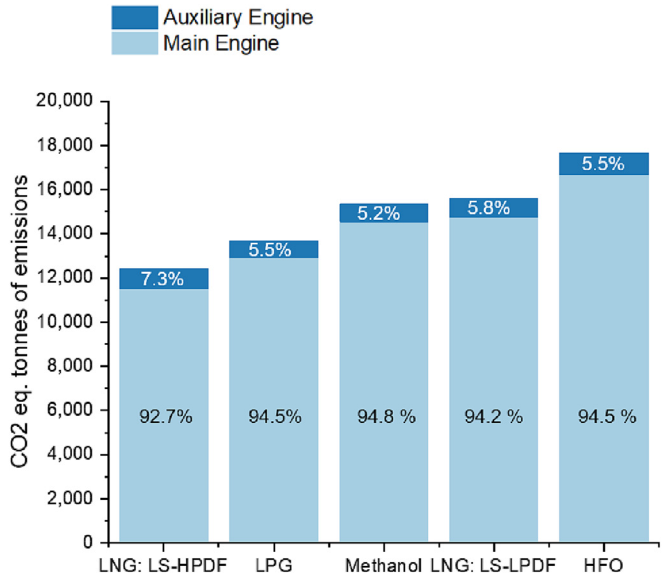


Fig. 10. Annual TtW GHG emissions for HFO, LNG, LPG and methanol fuel (at average main engine load: 72.5 % of MCR and operation days at sea: 250 days).

250 days at each engine load. At all engine loads, the main engine using HFO tends to emit the highest amount of GHGs, with the gap between HFO and other fuels in GHG emissions widening as engine load increases. It is also important to note that the emission characteristics of each fuel vary depending on the engine load. Specifically, at engine loads exceeding 80 %, methanol tends to produce steeper increases in GHG emissions compared to LNG with LS-LPDF. For example, at an engine load of 70 %, methanol and LS-LPDF emit 13,981.95 and 14,237.66 tons of greenhouse gases, respectively. At an engine load of 80 %, the emissions for methanol and LS-LPDF are 16,344.97 and 16,225.77 tons, respectively. These findings suggest that the load-dependent cubic function of specific fuel oil consumption for methanol is responsible for these differences, which distinguishes it from other fuels that exhibit quadratic functions Please see Table S26 in the supplement for more details.

4.3. Comparison of WtW GHG emissions

Fig. 14 shows the average WtW GHG emission that combines the results of Section 3.1 and 3.2. From the perspective of WtW GHG emission, LPG is the lowest while methanol counterpart is the largest. The results also clearly show that the emissions of selected fossil-based fuels for WtT phase have less influence on the overall WtW GHG emissions than TtW emissions, while their relative variances are higher. In particular, WtT contributions to the total ranged from 12.3 % with 11.15 g/MJ (HFO) to 33.06 % with 31.26 g/MJ (Methanol). This also inferred that GHG emissions are mainly derived from combustion processes from ship's engine using fossil fuel with significant carbon contents.

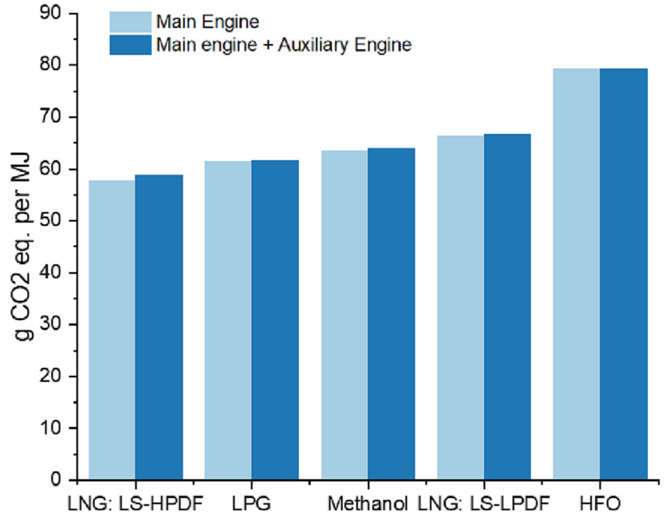


Fig. 11. Average GHG intensity of the energy used on board ships.

Table 10
Specific fuel consumption (g/kWh) for main fuel and pilot fuel depending on engine load.

Main engine load (%)	LNG fueled engine (LS-HPDF)		LNG fueled engine (LS-LPDF)		LPG fueled engine		Methanol engine	
	SFOC	SPOC	SFOC	SPOC	SFOC	SPOC	SFOC	SPOC
10	141.4	12.5	156.8	4.7	142.9	25.0	288.4	45.9
20	137.1	10.1	152.6	4.1	141.1	20.1	298.1	33.3
30	133.8	8.0	149.1	3.5	139.7	15.9	303.7	25.1
40	131.4	6.3	146.3	2.9	138.7	12.5	306.3	20.8
50	129.8	5.0	144.1	2.5	138.2	9.9	307.1	19.7
60	129.2	4.1	142.6	2.1	138.2	8.0	307.3	21.3
70	129.4	3.5	141.7	1.8	138.5	6.8	308.0	24.8
80	130.6	3.3	141.5	1.6	139.3	6.3	310.6	29.9
90	132.7	3.5	142.0	1.5	140.6	6.6	316.2	35.8
100	135.6	4.1	143.1	1.4	142.3	7.7	326.0	41.9

As a result, from a life cycle perspective, it is clear that LPG and LNG are fuels that can reduce GHG emissions compared to conventional fossil fuels (HFO) and methanol.

4.4. Comparison on impact of maritime transportation

To investigate the impact of lifecycle emissions associated with the regions of import, the three functional units of LNG fuel were examined as mentioned in Section 3.2.3.

As indicated in Table 5, the LNG import to Korea from Malaysia, Indonesia, and Australia is generally undertaken by 125 K LNGCs with steam turbine. Fig. 15 depicts the comparative analysis of average GHG emissions for these three units, namely E_c, E_d and E_{tw}. E_d and E_{tw} exhibit a similar trend across the three countries. In general, there seem little differences on emission levels across the importing countries. However, when applying E_c (emissions per LNG ton or MJ carried), commonly applied in LCA, Australia has a higher tendency on emission levels compared to Malaysia and Indonesia. This suggests that the analyzed 125 K LNG carriers operating between South Korea and Indonesia, or Malaysia have shorter voyage distances compared to the operational range on the Australia route, as illustrated in Fig. 16.

On the other hand, ships equipped with greater cargo capacity and more efficient propulsion systems typically emit lower amounts of GHG per unit of transport work(E_{tw}). These ships also demonstrate greater energy efficiency in their operations (IMO, 2020). For example, the utilization of steam turbine propulsion is associated with several disadvantages, such as low efficiency and a relatively high level of GHG emissions (Fernández et al., 2017).

A straightforward comparison of Etw between 125 K LNG carriers equipped with a steam turbine and 174 K LNG carriers utilizing LS-HPDP for LNG transportation to Korea, as illustrated in Fig. 15 and Fig. 17, unequivocally demonstrates the higher efficiency of the latter. However, it should be noted that this study does not investigate the specific influence of cargo capacity and propulsion systems on GHG emissions, and thus, their individual impacts remain unknown. This aspect is further discussed in Section 5.3 Limitations and Future Research Directions. Nevertheless, it is worth noting that the Ec of functional unit applied in the LCA, namely 'emissions per LNG ton or MJ carried' shows the opposite result: importing LNG from the USA via the 174 K LNGC, which not only has high propulsion efficiency but also a large cargo capacity, results in higher GHG emission levels in terms of Ec. This increase in emissions is likely due to the higher

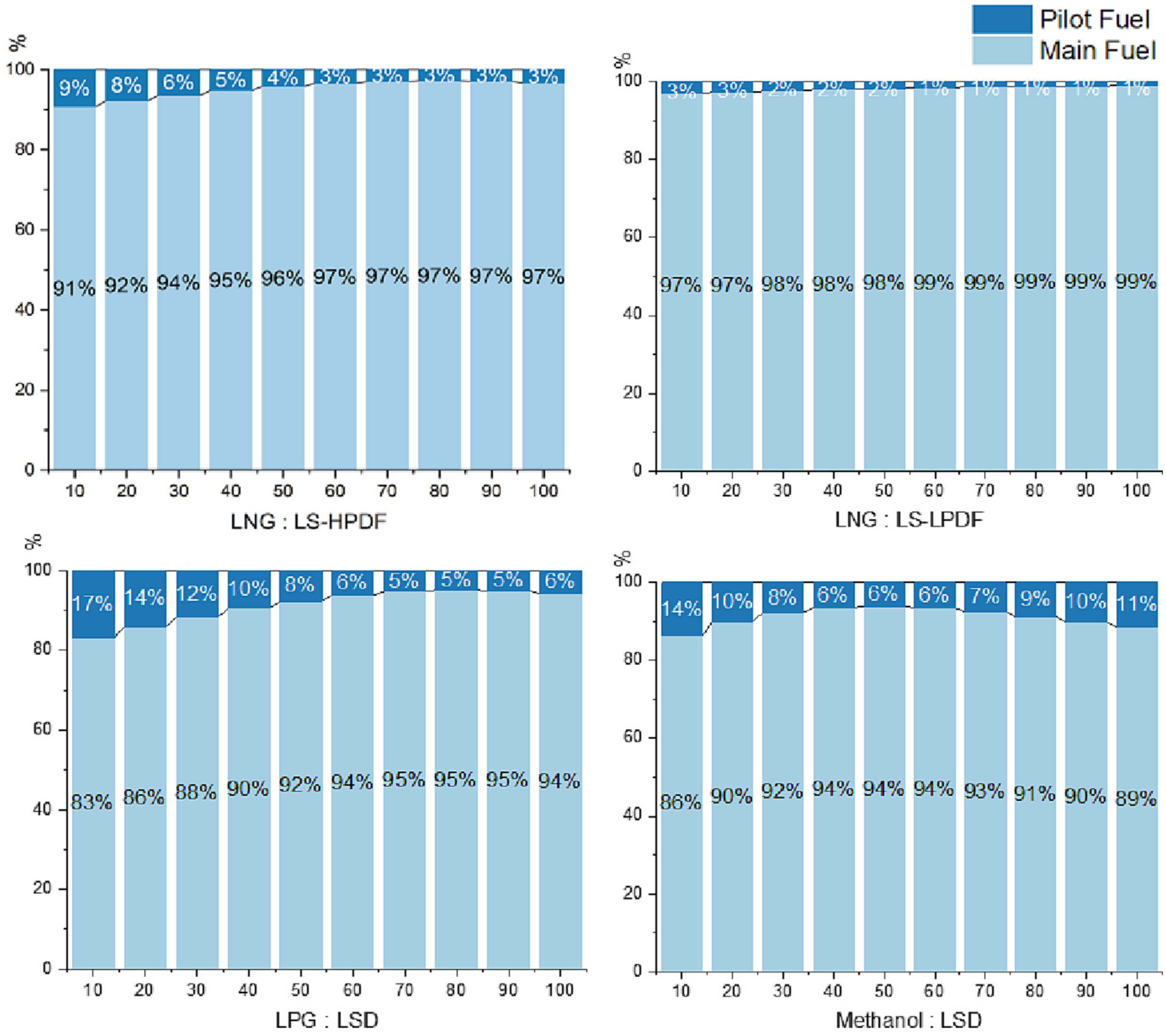


Fig. 12. Ratio of GHG emissions emitted by main fuel and pilot fuel depending on engine load.

voyage miles to South Korea, as shown in Fig. 16. Hence, the distance from the energy source can have a relatively significant impact on GHG emissions per LNG ton or MJ carried.

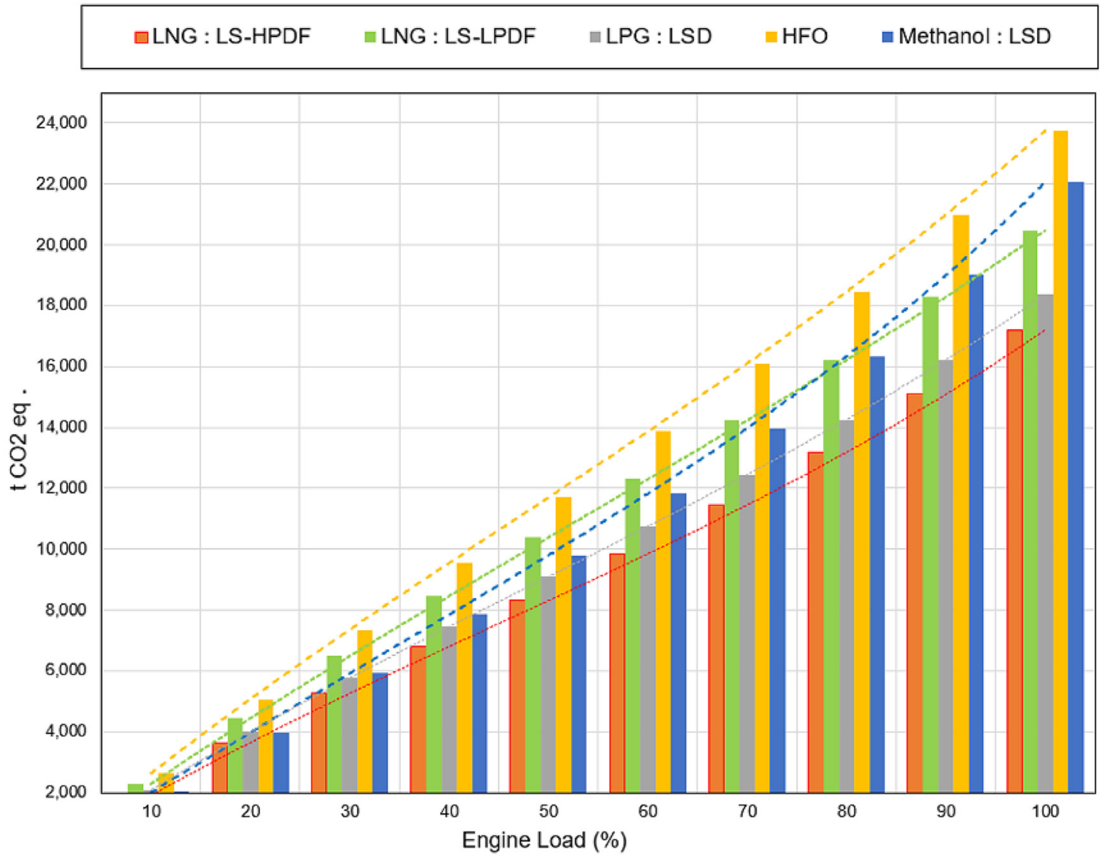
5. Discussion

In this section, the contributions and limitations of the study, and the direction of future research are presented.

5.1. Contribution to enhancing the understanding on current GHG emission level

The decarbonization of the shipping industry plays a crucial role in tackling the global issue of climate change. Given the fact that the shipping industry has been focusing only on GHG emissions from ships, the life cycle approach to evaluating GHG emissions from ship fuel is regarded as an effective policy measure for promoting low-carbon and zero-carbon fuels in the industry, taking into consideration not only the fuel use emissions but also the upstream emissions. It is essential for policymakers to understand current WtW emissions values, specifically those associated with the use of fossil fuels, before setting targets for reducing greenhouse gas emissions. In this context, the outcomes from this study would serve as a new standard for future comparison with renewable sustainable fuels to be introduced and contribute to the assessment of policy effectiveness over time. This research has also demonstrated significant variations in upstream emissions across countries, despite the use of identical fossil-based fuels. It also highlights that the selection of environmentally beneficial fuels in terms of ship's emissions alone may not necessarily result in substantial reductions in emissions levels, as these are also contingent on the production methods, source of energy, and countries of origin of the fuel. For instance, HFO WtT emission values, based on crude oil imported from Iraq and Saudi Arabia, show a notable discrepancy of about 220 %, with values of 16.2 g/MJ and 7.3 g/MJ, respectively. This difference highlights the potential implications on the significance of considering the emission level of the produced countries of crude oil as part of the decarbonization efforts.

On the other hand, from the perspective of countries that rely on energy imports, such as South Korea, the growing implementation of alternative fuels in international shipping can also be perceived as a reduction in the GHG emissions arising from the transportation of fuels into the country.



🟧 LNG : LS-HPDF	1,911	3,648	5,261	6,800	8,313	9,849	11,458	13,189	15,091	17,214
🟩 LNG : LS-LPDF	2,288	4,440	6,485	8,456	10,384	12,301	14,238	16,226	18,297	20,482
◼ LPG : LSD	2,090	3,997	5,770	7,454	9,098	10,750	12,456	14,263	16,220	18,374
🟨 HFO	2,637	5,071	7,358	9,551	11,703	13,870	16,105	18,463	20,997	23,762
🟦 Methanol : LSD	2,005	3,977	5,919	7,850	9,804	11,827	13,982	16,345	19,007	22,072

Fig. 13. GHG emissions from main engine using HFO, LNG, methanol and LPG fuel.

By analyzing the proportion of GHG emission by international maritime transportation in total WtW emission of the available fuels, this study enables us to anticipate the extent to which the decarbonization of international shipping can enhance or contribute to the WtW aspect of marine fuel produced in South Korea.

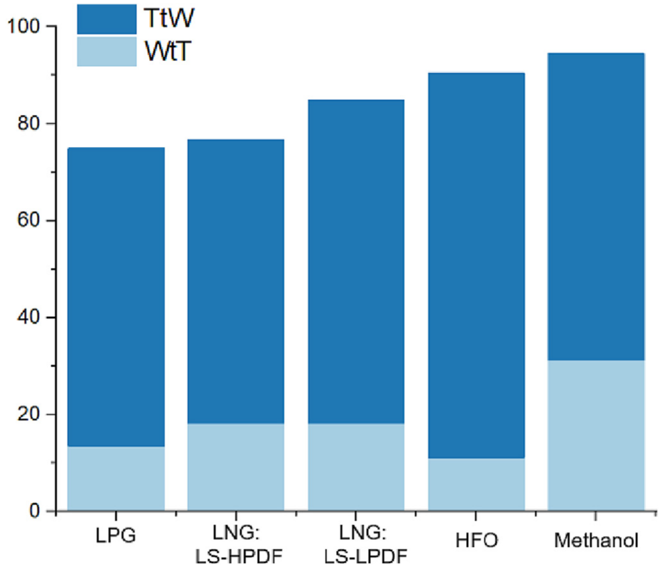


Fig. 14. WtW GHG emissions for HFO, LNG, methanol and LPG fuel.

5.2. Contribution to suggesting the future national and regional LCA regulatory framework for marine fuels

Given that the uptake of sustainable alternative fuels is paramount for the decarbonization of the shipping industry, this study has been driven by the strong needs of a government body, the Ministry of Oceans and Fisheries, which endeavors to determine the most suitable marine fuels. To satisfy these needs and answer the research questions, the study investigated the fuel pathways of currently available fuels and their relevant engine technologies, and analyzed their environmental performance to make the best choice.

Energy-importing countries like South Korea have lacked available and reliable life cycle emission data on marine fuels, resulting in a reliance on simple databases (e.g. GaBi and GREET) with varying situations and assumptions. Therefore, developing a customized database and proper emission model was critical work that could serve as a basis for formulating of firmly established policies for reducing GHG emissions in the shipping sector. Evidently, the case study has demonstrated the efficacy of the proposed emission model through a thorough examination of reliable data and scenarios that are more suitable for its country like South Korea. The functionality for impact analysis in Section 4.4 has demonstrated excellent capabilities for understanding the influence of geographic differences (e.g., voyage distance) on overall maritime GHG emissions, although their impact on the WtW GHG emissions is relatively small.

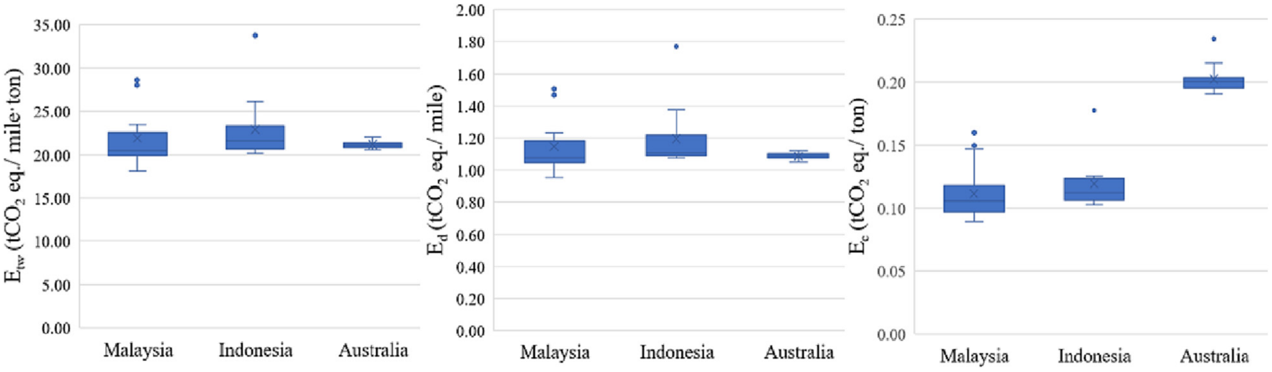


Fig. 15. Comparison of GHG Emissions in LNG transportation to Korea via 125 K LNGCs from Malaysia, Indonesia, and Australia.

In fact, there has been no research that proposed default value on marine fuel for the specific countries and international shipping sectors among LCA studies so far. In addition, as discussing the matters on the uncertainty and variations stemming from differences in geographical locations across nations and their supply routes and methods, the research findings are believed to be valuable guidance for the government who are subjected to setting the proper baseline for regulating the proper limit of the lifecycle GHG emission considering various fuels options. In establishing baseline or default values, the use of conservative values rather than average performance enables operators to provide certified actual values, leading to improved knowledge and reduced uncertainty. For example, Fig. 18 is a Sankey diagram showing variable GHG performance of fuels applied in this study are produced. The baseline (100 %) was based on the largest emitter of HFO produced from crude oil imported from Iran.

The FuelEU Maritime set the target on GHG intensity of energy and fuel used by 2 % in 2025 and increase it to 80 % by 2050, with interim targets of 14.5 % in 2035 and 31 % in 2040. If these targets were applied to marine fuels imported to South Korea, only the LPG fuel pathway and the LNG pathway with LS-HPDF are capable of achieving their 2035 targets, regardless of the production region investigated. Moreover, the targets could also be met for LS-HPDF with the LNG produced from specific regions, as depicted in Fig. 18.

Therefore, the research results, with the Sankey diagram, could be an excellent indicator for estimation the current levels of the emissions from use of fossil-based fuels and their potential reductions based on applied technologies with maturity. Additionally, this study provides fuel producers and engine makers with constructive recommendations for improving their emissions and achieving emission reduction targets. Although this paper is focused on South Korean case, it was suggested as an urgent task to stretch case studies on other countries to various regulatory bodies that require appropriate setting targets for GHG reduction.

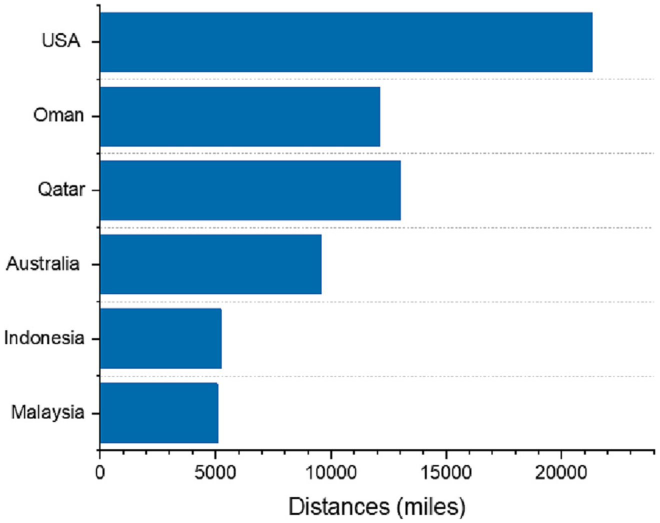


Fig. 16. Variations in voyage distances based on regions of LNG import.

From an IMO regulatory standpoint, the IMO framework employs global default values for fossil fuel pathways in the LCA methodology as the initial option, with the potential for utilizing regional factors upon stabilization. In this context, it also contributes to establishing regional values if global values are deemed limiting.

Overall, this study affirms and argues, through a case study, that WtT and TtW emission values should be developed based on a unified methodology. This study presents a novel approach and direction for environmental evaluation in the life cycle aspect, which is being considered as an alternative to the current regulation that is solely centered on the user's point of view. Moreover, by intuitively illustrating the significant environmental impacts of various import routes in the process of importing, refining, and utilizing fuel from a holistic perspective, this study demonstrates the urgent need for the introduction of a life cycle evaluation system for ship fuels. The outcomes of this study are significant and impactful, and they can be implemented in policies and regulations as an enhanced format of LCA application to the maritime sector. Meanwhile, it should be mentioned that the proposed LCA approach is useful for facilitating general observations on LCA impacts across various countries and regions. In addition to South Korean case, a series of other case studies should be followed to achieve this goal.

Last but not least, as a key contribution, research approaches and findings were documented and presented before IMO policy makers during IMO Marine Environment Protection Committee (MEPC) - 80th session. As a next step, it is paramount to take a further consideration on how the proposed method/model could be incorporated into IMO LCA guidelines which are currently under further development.

5.3. Limitation and future study directions

As depicted in Fig. 18 The pathway of lifecycle GHG emission for marine fuels imported to South Korea, the utilization of fossil-fuel-based marine fuels, which is the focal point of this study, indicates that there are restrictions to the transition to zero-emission shipping. It should be noted that selected fossil-based fuels exhibit significantly lower WtT emissions compared to TtW emissions. In other words, TtW emissions, which constitute the majority of WtW emissions, can only be reduced to a limited extent with fossil fuels (e.g., LPG has 25 % lower emissions compared to HFO). To achieve significant GHG emission reductions by 2050, the use of alternative fuels is essential. Nonetheless, this paper provides knowledge not only for recognizing the current emission levels but also for identifying potential emission reductions in the near future, for example by opting for or converting to LNG and LPG or by constructing new ships with their respective propulsion systems. Additionally, it's worth noting that reducing GHG emissions does not solely rely on identifying emissions from fossil fuels and

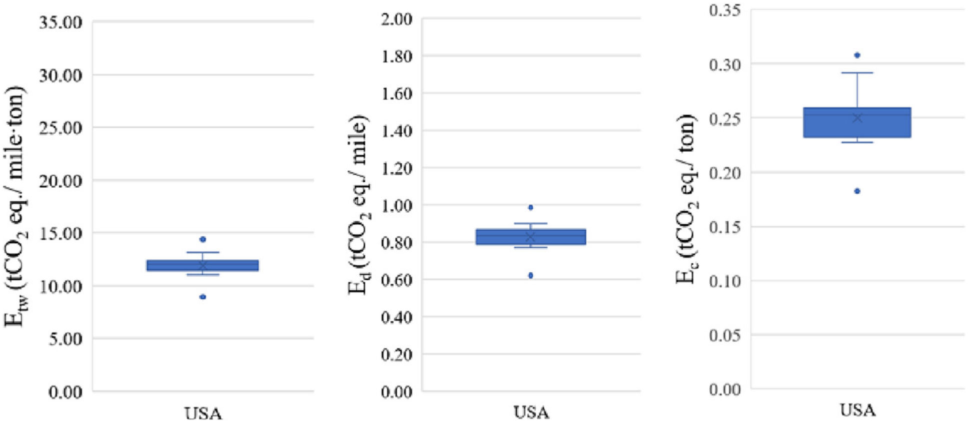


Fig. 17. Comparison of GHG Emissions in LNG transportation to Korea via 174 K LNGCs from USA.

setting reduction targets. It can also be accomplished by implementing quotas for alternative fuels (e.g., establishing a quota for synthetic aviation fuel in Europe).

The introduction of renewable fuels into the shipping sector has the capability to significantly mitigate life cycle GHG emissions (Deng et al., 2021). In particular, a shift from conventional fossil-based feedstock to renewable sources, such as biomass and renewable electricity, is imperative to achieve net zero emissions from the shipping sector by 2050 (Department for Transport (UK), 2021). However, due to the significant variations in the availability of renewable energy across regions and countries, further in-depth investigations are warranted to determine the most optimal renewable and sustainable fuel options from an LCA perspective, considering the unique energy scenarios of each nation's energy policy. Additionally, further research could be conducted to assess the potential impact for incorporating regional factors for renewable fuels into the LCA regulatory framework, based on emission level of fossil-based fuels presented in this study.

In addition, this study faced limitations in obtaining emission data, particularly regarding the WtT GHG emissions data for methanol production in certain regions. As a result, the study relied on available data for methanol production in the USA. To address this limitation, future research should prioritize the collection of comprehensive data on the WtT GHG emissions of methanol from different production regions, particularly the Middle East and Trinidad and Tobago. Investigating variations in production methods and associated emissions profiles is crucial to provide a more accurate assessment of the environmental impact of methanol production and

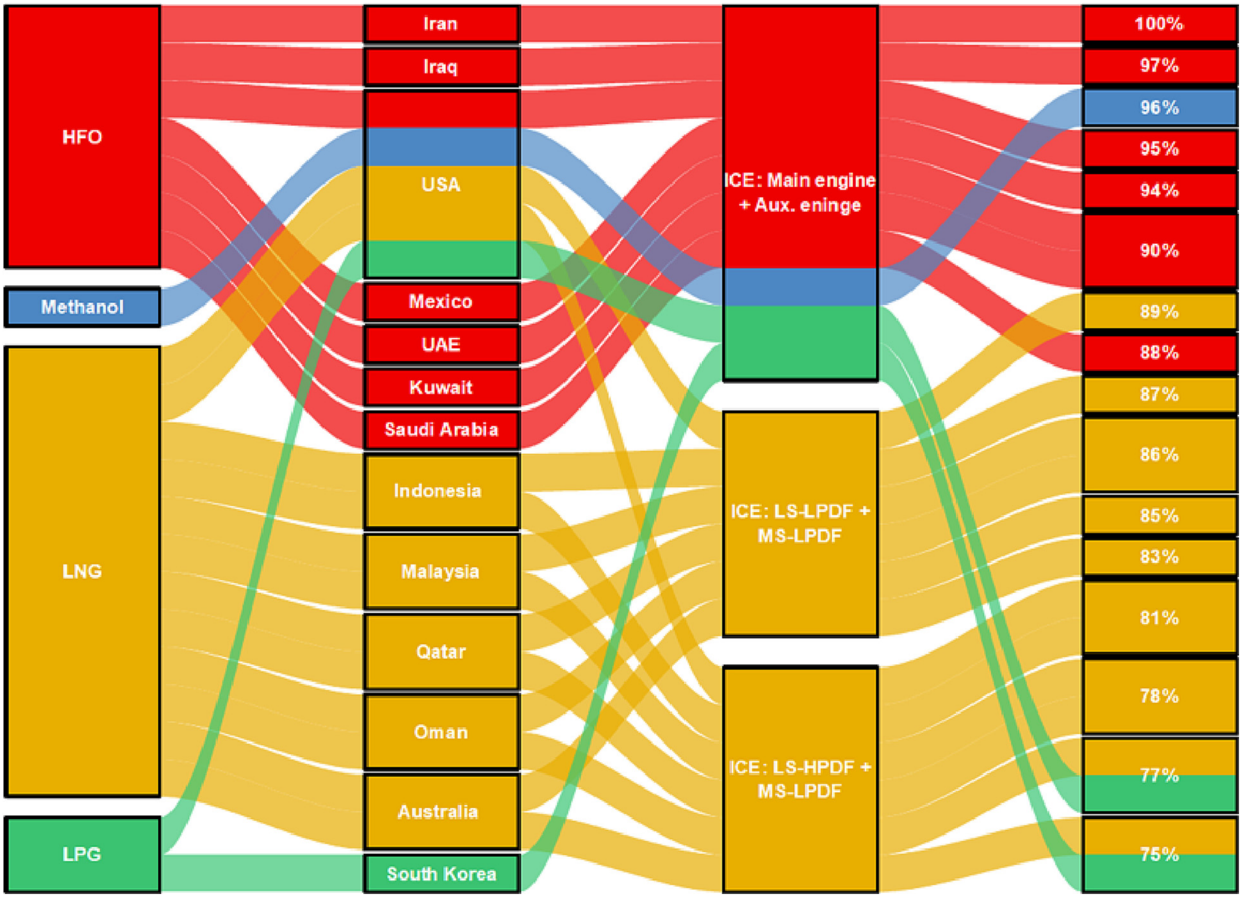


Fig. 18. The pathway of lifecycle GHG emission for marine fuels imported to South Korea.

transportation to South Korea. Furthermore, further investigation of GHG emissions from methanol transport by international shipping based on actual vessel operational data is also necessary.

Another limitation of this study is that, while this study investigated the general perspective on impact of geographical differences, specifically maritime transportation distances that reflect regional characteristics on the lifecycle emission levels, the specific influence of cargo capacity and propulsion systems on GHG emissions was not identified. Given that emissions associated with shipping activities vary depending on various parameters, including the transport route, ship capacity, total transported quantity, and engine type, further research is required to quantitatively assess how individual factors affect GHG emissions.

It should be noted that the main purpose of this LCA approach is to assist in the decision-making process regarding the proper selection of fuels and propulsion systems for ships. Even though the WTT value has been extensively studied and is known to have a relatively smaller impact on LCA, compared to TTW impacts, this does not necessarily limit the novelty of this study. This study is intended to be applicable not only to conventional fossil fuels, but also to low-carbon or zero-carbon fuels. In the case of alternative fuels, such as hydrogen made from natural gas, where the weight of the WtT emission is significant (DNV, 2018), the importance of the key parameters discussed in this paper would be magnified. In other words, although the interpretation of this case study may be limited, it would be beneficial to include in the discussion that when applying this LCA model to alternative fuels and their energy sources, where WTT has a decisive impact, the results will be significantly different and the impact will be even greater.

Last but not least, as a key contribution, research approaches and findings will be presented before IMO policy makers during IMO Marine Environment Protection Committee (MEPC). As a next step, it is paramount to take a further consideration on how the proposed method/model could be incorporated into IMO LCA guidelines which are currently under further development.

6. Conclusion

The novelty of this research can be placed on addressing the importance of developing robust default WtW emission values and evaluating the GHG performance of various marine fuels across the world. The South Korean case study has successfully come into the following conclusions:

- Among HFO, LNG, LPG and methanol fuels, TtW GHG emissions from the HFO-fueled ship were the greatest while using LNG with LS-HPDF was the lowest.
- In the case of using dual fuel engines, changing pilot fuels to renewable fuels like bio-fuel and synthetic fuel can contribute to reducing TtW GHG emissions by 3 % (LNG: LS-LPDF) to 17 % (LPG), depending on the fuel and engine type, as well as engine load.
- The emissions generated by auxiliary engines account for between 5.2 % and 7.3 % of the total TtW GHG emissions. However, these emissions have minimal impact on the average total GHG intensity of the energy used on board ships, as long as the auxiliary engines and main engines use the same fuel.
- HFO comes to the forefront in terms of WtT GHG emission. Its GHG emission with 11.15 g/MJ would be 18.1 %, 38.5 %, and 64.3 % percent lower than those of the LPG, LNG, and methanol. However, the emissions of WtT phase have less influence on the overall WtW GHG emissions than TtW emissions, while their relative variance is higher. In particular, WtT contributions to the total ranged from 12.3 % with 11.15 g/MJ (HFO) to 33.1 % with 31.26 g/MJ (Methanol).
- The average WtW GHG emissions of LPG and LNG, which are fossil-based fuels, are generally lower than those of conventional fossil fuel (HFO) and methanol. LPG has the lowest emission levels, followed by LNG (LS-HPDF), LNG (LS-LPDF), HFO and methanol.
- The impact of international shipping for energy carriers on WtT GHG emissions would be, to some large extent, influenced by various factors: the propulsion systems, the quantity of energy transported, and the routes and distances of voyages from the origin country of energy imports. For LNG fuel, transportation emissions from LNG carriers can vary, ranging from 12.2 % of WtT emissions in the case of import from Malaysia (2.26 g CO_2 eq./MJ) to 33.3 % of WtT emissions when it comes from Qatar (5.97 g CO_2 eq./MJ).
- Furthermore, for the estimated WtW GHG emission of LNG fuel, the lowest value is observed for fuel imported from Australia, which emits 74.25 g CO_2 eq./MJ (WtT:15.46, TtW: 58.8 using LS-HPDF). On the other hand, the highest value was found for LNG imported from the USA, with emissions of 87.85 g CO2 eq./MJ (WtT: 21.06, TtW: 66.84 using LS-LPDF).
- WtW GHG emissions from HFO show a greater variation depending on the country of origin (100–88 %), whereas this effect is relatively small for other fuels, including LNG with LS-LPDF (89–83 %), methanol (96 %), LNG with LS-HPDF (81–75 %), and LPG (77–75 %). However, it is evident that depending on the fuel, a substantial reduction in WtW emissions can be achieved through TtW emissions due to their greater impact (LNG with LS-LPDF: 79 %, methanol: 67 %, LNG with LS-HPDF: 76 %, LPG: 82 %). Consequently, while WtW considerations provide a detailed perspective, it is ultimately the TtW emissions that play a more decisive role in reducing emissions when using fossil-based fuels.
- Overall, this paper highlights the importance of developing default values of GHG emissions for different countries. Research findings offer an insight into future LCA guidelines and academic/industrial practices that need to be further incorporated with the impact of regional or geographic characteristics, such as fuel production technologies and voyage distance in maritime transportation, in the WtT component and the choice of propulsion system in the TtW component. These parameters will contribute to developing unique default LCA values for each nation so that the accuracy and precision of the holistic assessment will be improved. Finally, decision/policy-making processes including market-based measurement i.e. FuelEU Maritime can be enhanced, leading to effective controls for curbing emissions from the transportation sector.

CRediT authorship contribution statement

Seongman Ha: Conceptualization, Design, Writing - original draft, Methodology, Software.

Byongug Jeong: Writing - review & editing, Investigation, proof reading.

Hayoung Jang: Writing - review & editing, Investigation, Design.

Chybyung park: Writing - review & editing, Proof reading, Design, Supervision.

Byungchurl Ku: Investigation, proof reading and Resources.

Data availability

Data will be made available on request.

Declaration of competing interest

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

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References

Adnan, M.A., Kibria, M.G., 2020. Comparative techno-economic and life-cycle assessment of power-to-methanol synthesis pathways. Appl. Energy 278, 115614.

Ampah, J.D., Yusuf, A.A., Afrane, S., Jin, C., Liu, H., 2021. Reviewing two decades of cleaner alternative marine fuels: towards IMO's decarbonization of the maritime transport sector. J. Clean. Prod. 320, 128871.

ARGUS. South Korean methanol trades below SE Asian prices. https://www.argusmedia.com/en/news/2432205-south-korean-methanol-trades-below-se-asian-prices (accessed 20 May 2023) 2023.

Bengtsson, S., Andersson, K., Fridell, E., 2011. A comparative life cycle assessment of marine fuels: liquefied natural gas and three other fossil fuels. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment 225, 97–110.

Bengtsson, S., Fridell, E., Andersson, K., 2012. Environmental assessment of two pathways towards the use of biofuels in shipping. Energy Policy 44, 451–463.

Bilgili, L., 2021. Life cycle comparison of marine fuels for IMO 2020 Sulphur Cap. Sci. Total Environ. 774, 145719.

Brandão, M., Clift, R., Cowie, A., Greenhalgh, S., 2014. The use of life cycle assessment in the support of robust (climate) policy making: comment on" using attributional life cycle assessment to estimate climate-change mitigation...". J. Ind. Ecol. 18, 461–463.

Brinks, H.W., Chryssakis, C., 2017. LPG as a Marine Fuel. DNV GL strategic research and position paper.

Brynolf, S., Fridell, E., Andersson, K., 2014. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. J. Clean. Prod. 74, 86–95.

Carvalho, F.S., Lacava, P.T., Rufino, C.H., Pedroso, D.T., Machin, E.B., Araújo, F.H., et al., 2023. Mixtures of heavy fuel oil and green hydrogen in combustion equipment: energy analysis, emission estimates, and economic prospects. Energy Convers. Manag. 277, 116629.

Chen, Z.S., Lam, J.S.L., 2022. Life cycle assessment of diesel and hydrogen power systems in tugboats. Transp. Res. Part D: Transp. Environ. 103, 103192.

Chester, M.V., Cano, A., 2016. Time-based life-cycle assessment for environmental policymaking: greenhouse gas reduction goals and public transit. Transp. Res. Part D: Transp. Environ. 43, 49–58.

Choi, W., Song, H.H., 2014. Well-to-wheel analysis on greenhouse gas emission and energy use with natural gas in Korea. Int. J. Life Cycle Assess. 19, 850–860.

Choi, W., Yoo, E., Seol, E., Kim, M., Song, H.H., 2020. Greenhouse gas emissions of conventional and alternative vehicles: predictions based on energy policy analysis in South Korea. Appl. Energy 265, 114754.

Comer, B., Osipova, L., 2021. Accounting for Well-to-Wake Carbon Dioxide Equivalent Emissions in Maritime Transportation Climate Policies. International Council on Clean Transportation.

Dale, B.E., Kim, S., 2014. Can the predictions of consequential life cycle assessment be tested in the real world? Comment on "using attributional life cycle assessment to estimate climate-change mitigation...". J. Ind. Ecol. 18, 466–467.

de Fournas, N., Wei, M., 2022. Techno-economic assessment of renewable methanol from biomass gasification and PEM electrolysis for decarbonization of the maritime sector in California. Energy Convers. Manag. 257, 115440.

Deng, J., Wang, X., Wei, Z., Wang, L., Wang, C., Chen, Z., 2021. A review of NOx and SOx emission reduction technologies for marine diesel engines and the potential evaluation of liquefied natural gas fuelled vessels. Sci. Total Environ. 766, 144319.

Department for Transport (UK). The Role of the RTFO in Domestic Maritime. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/974823/annex-a-the-role-of-the-rtfo-in-domestic-maritime.pdf [accessed 13 July 2022] 2021.

DNV, 2018. Assessment of Selected Alternative Fuels and Technologies. DNV GL—Maritime.

DNV. Comparison of alternative marine fuels. For SEALNG, DNV GL report 2019a.

DNV. https://www.dnv.com/expert-story/maritime-impact/Making-LPG-fuel-an-option-for-the-shipping-industry.htmlMaking (Accessed 30 October 2022). 2019b.

DNV, 2022. Alternative Fuels Insight.

Domić, I., Stanivuk, T., Stazić, L., Pavlović, I., 2022. Analysis of lng carrier propulsion developments. Journal of Applied Engineering Science 20, 1122–1132.

Earles, J.M., Halog, A., 2011. Consequential life cycle assessment: a review. Int. J. Life Cycle Assess. 16, 445–453.

Ekvall, T., 2019. Attributional and Consequential Life Cycle Assessment. Sustainability Assessment at the 21st Century. IntechOpen.

El-Houjeiri, H., Monfort, J.C., Bouchard, J., Przesmitzki, S., 2019. Life cycle assessment of greenhouse gas emissions from marine fuels: a case study of Saudi crude oil versus natural gas in different global regions. J. Ind. Ecol. 23, 374–388.

Fernández, I.A., Gómez, M.R., Gómez, J.R., Insua, Á.B., 2017. Review of propulsion systems on LNG carriers. Renew. Sust. Energ. Rev. 67, 1395–1411.

Fernández-Ríos, A., Santos, G., Pinedo, J., Santos, E., Ruiz-Salmón, I., Laso, J., et al., 2022. Environmental sustainability of alternative marine propulsion technologies powered by hydrogen-a life cycle assessment approach. Sci. Total Environ. 820, 153189.

Fun-sang Cepeda, M.A., Pereira, N.N., Kahn, S., Caprace, J.-D., 2019. A review of the use of LNG versus HFO in maritime industry. Marine Systems & Ocean Technology 14, 75–84.

Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K., Murphy, A., 2018. Assessment of full life-cycle air emissions of alternative shipping fuels. J. Clean. Prod. 172, 855–866.

Hertwich, E., 2014. Understanding the climate mitigation benefits of product systems: comment on "using attributional life cycle assessment to estimate climate-change mitigation…". J. Ind. Ecol. 18, 464–465.

Holzer, K.K., Muirhead, J.R., Minton, M.S., Carney, K.J., Miller, A.W., Ruiz, G.M., 2017. Potential effects of LNG trade shift on transfer of ballast water and biota by ships. Sci. Total Environ. 580, 1470–1474.

Hwang, S., Jeong, B., Jung, K., Kim, M., Zhou, P., 2019. Life cycle assessment of LNG fueled vessel in domestic services. Journal of Marine Science and Engineering 7, 359.

ICAO. CORSIA Supporting Document—CORSIA Eligible Fuels—Life Cycle Assessment Methodology. 2019.

IMO. Guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships. International Maritime Organization London, UK, 2018a.

IMO. Initial IMO strategy on reduction of GHG emissions from ships. International Maritime Organization. Resolution MEPC.304(72) 2018b.

IMO. Fourth IMO GHG Study 2020. International Maritime Organization (IMO) London, UK, 2020.

IMO, 2021. Updated Draft Lifecycle GHG and Carbon Intensity Guidelines for Maritime Fuels, ISWG-GHG 9/2/3. Norway and ICS, Australia, Japan.

IMO. MEPC 78/WP.5, Report of the eleventh meeting of the Intersessional Working Group on Reduction of GHG Emissions from Ships (ISWG-GHG 11), 2022a.

IMO. MEPC 78/WP.6, Report of the twelfth meeting of the Intersessional Working Group on Reduction of GHG Emissions from Ships (ISWG-GHG 12), 2022b.

IMO. Proposal for a GHG Fuel Standard, ISWG-GHG 12/3/3 (EU), 2022c.

IMO. Res. MEPC.346(78)), 2022 Guidelines For The Development Of A Ship Energy Efficiency Management Plan (SEEMP). 2022d.

Jang, H., Jeong, B., Zhou, P., Ha, S., Nam, D., 2021. Demystifying the lifecycle environmental benefits and harms of LNG as marine fuel. Appl. Energy 292, 116869.

Jang, J.J., Song, H.H., 2015. Well-to-wheel analysis on greenhouse gas emission and energy use with petroleum-based fuels in Korea: gasoline and diesel. Int. J. Life Cycle Assess. 20, 1102–1116.

Kim, K., Moon, S., Lee, J., Kim, J., 2023. Environmental impacts of transportation policy and vehicle market share predictions. Transp. Res. Part D: Transp. Environ. 114, 103550.

KOGAS, 2020. www.kogas.or.kr.

Korea Petroleum Association, 2022. http://www.petroleum.or.kr/ko/.

KOSIS. Statistics of petroleum supply and demand, Korean Statistical Information Service, http://kosis.kr/statHtml/statHtml.do?orgId = 318&tblId = TX_31801_A012. accessed 01.10.22, 2022.

Kouzelis, K., Frouws, K., van Hassel, E., 2022. Maritime fuels of the future: what is the impact of alternative fuels on the optimal economic speed of large container vessels. Journal of Shipping and Trade 7, 1–29.

Lenzen, M., Tzeng, M., Floerl, O., Zaiko, A., 2023. Application of multi-region input-output analysis to examine biosecurity risks associated with the global shipping network. Sci. Total Environ. 854, 158758.

Lindstad, E., Rialland, A., 2020. LNG and cruise ships, an easy way to fulfil regulations—versus the need for reducing GHG emissions. Sustainability 12, 2080.

Lindstad, E., Lagemann, B., Rialland, A., Gamlem, G.M., Valland, A., 2021. Reduction of maritime GHG emissions and the potential role of E-fuels. Transp. Res. Part D: Transp. Environ. 101, 103075.

Malmgren, E., Brynolf, S., Fridell, E., Grahn, M., Andersson, K., 2021. The environmental performance of a fossil-free ship propulsion system with onboard carbon capture–a life cycle assessment of the HyMethShip concept. Sustainable Energy & Fuels 5, 2753–2770.

MAN Energy Solutions. Using Methanol Fuel in the MAN B&W ME-LGI Series. Copenhagen, 2014.

MAN Energy Solutions. Methanol-fueled MAN B&W LGIM Engine. 2021.

MAN Energy Solutions. At the Forefront of Green Engine Technology. 2023. MAN Energy Solutions, 2020.

Manouchehrinia, B., Dong, Z., Gulliver, T.A., 2020. Well-to-propeller environmental assessment of natural gas as a marine transportation fuel in British Columbia. Canada. Energy Reports 6, 802–812.

Marketa, P., 2022. Sustainable Maritime Fuels-'Fit for 55'package: The FuelEU Maritime Proposal.

Martin, A., 2021. A Step Forward for Green Methanol and Its Potential to Deliver Deep GHG Reductions in Maritime Shipping. International Council on Clean Transportation.

Masnadi, M.S., El-Houjeiri, H.M., Schunack, D., Li, Y., Englander, J.G., Badahdah, A., et al., 2018. Global carbon intensity of crude oil production. Science 361, 851–853.

Mavrelos, C., Theotokatos, G., 2018. Numerical investigation of a premixed combustion large marine two-stroke dual fuel engine for optimising engine settings via parametric runs. Energy Convers. Manag. 160, 48–59.

MOL. MOL's New App Boosts Efficiency with Real-time Processing of Ship Operational Data, 2022.

Moretti, C., Corona, B., Hoefnagels, R., van Veen, M., Vural-Gürsel, I., Strating, T., et al., 2022a. Kraft lignin as a bio-based ingredient for Dutch asphalts: an attributional LCA. Sci. Total Environ. 806, 150316.

Moretti, C., Vera, I., Junginger, M., López-Contreras, A., Shen, L., 2022b. Attributional and consequential LCAs of a novel bio-jet fuel from Dutch potato by-products. Sci. Total Environ. 813, 152505.

Ortega, A., Gkoumas, K., Tsakalidis, A., Pekár, F., 2021. Low-emission alternative energy for transport in the EU: state of play of research and innovation. Energies 14, 7764.

Pavlenko, N., Comer, B., Zhou, Y., Clark, N., Rutherford, D., 2020. The Climate Implications of Using LNG as a Marine Fuel. Berlin, Germany, International Council on Clean Transportation.

Perčić, M., Vladimir, N., Fan, A., 2020. Life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-sea shipping: a case study of Croatia. Appl. Energy 279, 115848.

Pham, V.C., Rho, B.-S., Kim, J.-S., Lee, W.-J., Choi, J.-H., 2021. Effects of various fuels on combustion and emission characteristics of a four-stroke dual-fuel marine engine. Journal of Marine Science and Engineering 9, 1072.

Plevin, R.J., Delucchi, M.A., Creutzig, F., 2014. Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers. J. Ind. Ecol. 18, 73–83.

Prapaspongsa, T., Gheewala, S.H., 2017. Consequential and attributional environmental assessment of biofuels: implications of modelling choices on climate change mitigation strategies. Int. J. Life Cycle Assess. 22, 1644–1657.

Schaubroeck, T., Schaubroeck, S., Heijungs, R., Zamagni, A., Brandão, M., Benetto, E., 2021. Attributional & consequential life cycle assessment: definitions, conceptual characteristics and modelling restrictions. Sustainability 13, 7386.

Schuller, O., Reuter, B., Hengstler, J., Whitehouse, S., Zeitzen, L., 2017. Greenhouse Gas Intensity of Natural Gas, Thinkstep AG. Natural & Bio Gas Vehicle Association. NGVA, Europe.

Schuller, O., Kupferschmid, S., Hengstler, J., Whitehouse, S., 2019. Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel. Stuttgart, Germany, Hinkstep.

Seddiek, I.S., Ammar, N.R., 2023. Technical and eco-environmental analysis of blue/green ammonia-fueled RO/RO ships. Transp. Res. Part D: Transp. Environ. 114, 103547.

Seithe, G.J., Bonou, A., Giannopoulos, D., Georgopoulou, C.A., Founti, M., 2020. Maritime transport in a life cycle perspective: how fuels, vessel types, and operational profiles influence energy demand and greenhouse gas emissions. Energies 13, 2739.

Sharafian, A., Blomerus, P., Mérida, W., 2019. Natural gas as a ship fuel: assessment of greenhouse gas and air pollutant reduction potential. Energy Policy 131, 332–346.

Smith, T., Jalkanen, J., Anderson, B., Corbett, J., Faber, J., Hanayama, S., et al., 2015. Third Imo Ghg Study.

Spoof-Tuomi, K., Niemi, S., 2020. Environmental and economic evaluation of fuel choices for short sea shipping. Clean Technologies 2, 34–52.

Strazza, C., Del Borghi, A., Costamagna, P., Traverso, A., Santin, M., 2010. Comparative LCA of methanol-fuelled SOFCs as auxiliary power systems on-board ships. Appl. Energy 87, 1670–1678.

Sun, Z., Aziz, M., 2021. Comparative thermodynamic and techno-economic assessment of green methanol production from biomass through direct chemical looping processes. J. Clean. Prod. 321, 129023.

Thaler, B., Kanchiralla, F.M., Posch, S., Pirker, G., Wimmer, A., Brynolf, S., et al., 2022. Optimal design and operation of maritime energy systems based on renewable methanol and closed carbon cycles. Energy Convers. Manag. 269, 116064.

Thinkstep. Emission Study on the Use of LNG as Marine Fuel, 2019.

Turnau, S., Mignot, C.S., Mostert, C., Bringezu, S., 2020. Material or fuel: comparative cradle-to-grave climate and material footprint analysis for the use of methanol from recycled CO 2. Green Chem. 22, 8423–8443.

U.S. Energy Information Agency. Country Analysis Executive Summary: South Korea, https://www.eia.gov/international/analysis/country/KOR (accessed 31 October 2022). 2019.

Vázquez-Rowe, I., Marvuglia, A., Rege, S., Benetto, E., 2014. Applying consequential LCA to support energy policy: land use change effects of bioenergy production. Sci. Total Environ. 472, 78–89.

Wang M, Elgowainy A, Lee U, Bafana A, Banerjee S, Benavides PT, et al. Summary of Expansions and Updates in GREET® 2021. Argonne National Lab.(ANL), Argonne, IL (United States), 2021.

WIN GD. Gas Technology. 2023. WIN GD, 2021.

Winebrake, J.J., Corbett, J.J., Umar, F., Yuska, D., 2019. Pollution tradeoffs for conventional and natural gas-based marine fuels. Sustainability 11, 2235.

WLPGA. Guide to LPG Use in Water Borne Vessels 2017.

WLPGA. LPG as a marine fuel: What are the key drivers and barriers? https://safety4sea.com/cm-lpg-as-a-marine-fuel-what-are-the-key-drivers-and-barriers/ (accessed 13 October 2022) 2021.

Yuan, Y., Zhang, Y., Mao, J., Yu, G., Xu, K., Zhao, J., et al., 2023. Diverse changes in shipping emissions around the Western Pacific ports under the coeffect of the epidemic and fuel oil policy. Sci. Total Environ., 162892

Zamagni, A., Guinée, J., Heijungs, R., Masoni, P., Raggi, A., 2012. Lights and shadows in consequential LCA. Int. J. Life Cycle Assess. 17, 904–918.

Zhao, J., Wei, Q., Wang, S., Ren, X., 2021. Progress of ship exhaust gas control technology. Sci. Total Environ. 799, 149437.