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Advancement of Life Cycle Assessment Policy Framework on Marine Fuels towards Decarbonisation in the Shipping Sector

by

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

To my family: my wife, Youngseon; my son, Junwoo; and my daughter, Yeonjae

To my UK family: Jim and Sandra

To my company: Korean Register

ABSTRACT

In response to the urgent need for decarbonization in international shipping, the International Maritime Organization (IMO) is developing a life cycle assessment (LCA) framework for marine fuels to encourage the adoption of cleaner alternatives. This thesis critically examines LCA's role in maritime decarbonization, stressing the need for a sophisticated LCA policy framework. It identifies gaps in current policies and methodologies, emphasizing a harmonized LCA approach for consistent GHG emissions data.

An advanced LCA policy tailored for shipping decarbonization is developed and validated through case studies: 1) harmonization within the LCA regulatory framework, 2) determining life cycle GHG emissions of fossil marine fuels in energy-importing countries, 3) developing a prospective LCA framework for hydrogen-based e-fuels, and 4) formulating a GHG emissions accounting framework for sustainable marine fuel and onboard carbon capture.

The first study reveals gaps in current policies and LCA methodologies related to GHG reduction from marine fuels, underscoring the need for unified LCA frameworks. The second study shows that Well-to-Wake emission values and GHG performance evaluation are influenced by factors such as propulsion systems and the quantity of transported energy. The third case study on hydrogen-based e-fuel demonstrates the prospective LCA framework's effectiveness in predicting international shipping's GHG emissions alignment with existing targets. It explores sustainable fuel pathways, examining potential contributions towards meeting GHG reduction targets. The last case study presents a GHG emission accounting framework for sustainable marine fuel and onboard carbon capture, enhancing emission precision.

Conclusions emphasize the necessity of a unified LCA framework for shipping, the significant contribution of the prospective LCA framework, and the need for international collaboration. Validated through case studies, the framework challenges current rules for future regulatory frameworks, providing insights for

refining global LCA frameworks and urging a systematic approach to reduce GHG emissions in the maritime sector.

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GLOSSARY

ADP	Abiotic Depletion Potential
AER	Annual Efficiency Ratio
AFOLU	Agriculture, Forestry and Other Land Use sector
A-LCA	Attributional LCA modelling
AP	Acidification Potential
CAEP	The Committee on Aviation Environmental Protection
CEF	CORSIA Eligible Fuel
CH4	Methane
CII	Carbon Intensity Indicator
C-LCA	Consequential LCA modelling
CO2	Carbon Dioxide
CO2eq	Carbon Dioxide Equivalent Emissions
COP	Conference of the Parties Climate Summit
DCS	Data Collection System
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EEXI	Energy Efficiency Existing Ship Index
EP	Eutrophication Potential
GHG	Greenhouse Gases
HFO	Heavy Fuel Oil
HTP	Human Toxicity Potential
ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
IPCC	Intergovernmental Panel for Climate Change
ISSC	International Carbon and Sustainability Certification
LCA	Life Cycle Assessment
LCAF	Lower Carbon Aviation Fuels
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas

LSFO	Low Sulphur Fuel Oil
MARPOL	The International Convention for the Prevention of Pollution from Ships
MGO	Marine Gas Oil
N2O	Nitrogen Oxides
ODP	Ozone Layer Depletion Potential
PM	Particulate Matter
POCP	Photochemical Ozone Creation Potential
RED II	Renewable Energy Directive II
SAF	Sustainable Aviation Fuels
TtW	Tank-to-Wake
UNFCCC	United Nations Framework Convention on Climate Change
WtT	Well-to-Tank
WtW	Well-to-Wake

1 INTRODUCTION

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). However, global maritime transport faces a critical challenge: its significant contribution to climate change. Global Greenhouse Gas(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). This alarming trajectory threatens to exacerbate climate change, with potentially devastating consequences. 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 2023, the IMO further bolstered its commitment to GHG reduction by adopting a revised strategy with the aim of achieving net-zero GHG emissions by around 2050 (IMO 2023). To support this, the IMO has rolled out 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) and other CIIs for implementing a rating scheme as operational measure (IMO, 2022f). 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 Figure 1-1.

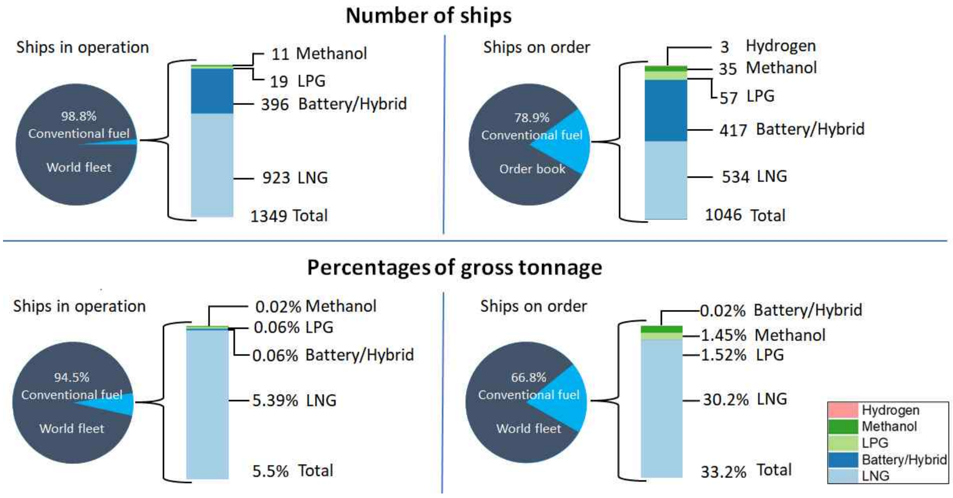


Figure 1-1. Alternative fuel uptake in the world fleet by number of ships, as adapted from (DNV, 2022)

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.

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

Although the maritime sector was excluded from the Paris Agreement, the IMO developed and presented a roadmap to support the Paris Agreement. They have enacted and implemented a series of stringent environmental regulations to reduce air pollutants that contribute to global warming, acid rain and even more. In particular, IMO MARPOL Annex VI contains regulations on curbing air pollution from ships including sulphur oxides (SO_x), nitrous oxides (NO_x), and ozone depleting substances (ODS) (International Maritime Organization, 2021).

Notwithstanding the enterprising stance, the efforts of IMO towards environmental protection have exhibited evident shortcomings. The IMO's focus has been solely on the emissions produced during fuel consumption, thereby neglecting other environmental factors that emerge throughout various stages such as production, transportation, and storage. Consequently, the policy has been viewed as one that disregards these aspects. Given this, the current IMO instruments have often provided a false confidence on using low or no carbon fuels. Ships using those fuels were simply considered as ‘zero emission’ ships. However, a huge amount of those fuels like hydrogen and ammonia are presently produced from fossil-based primary energy sources so that life cycle GHG impacts of them are still massive.

To remedy this, life cycle assessment (LCA) has drawn a strong attention to the marine sector. IMO and local governments are currently striving to develop an unified LCA model applicable for international shipping. In the realm of environmental impact assessments, the LCA is a pivotal methodology that systematically evaluates the environmental aspects and potential impacts associated with a product, process, or service throughout its life cycle. LCA considers all stages, from raw material extraction to production, use, and disposal. The goal is to provide a comprehensive understanding of the environmental footprint, aiding in informed decision-making for sustainable practices. For the maritime industry, this means understanding the environmental footprint of ships and the fuels they use, considering everything from raw material extraction to production, transportation, use, and disposal.

It also allows us to compare different marine fuels, products or processes. In particular, this can mean comparing the environmental impact of traditional fossil fuels with alternative fuels like hydrogen or biofuels. These comparisons are vital for making strategic choices that align with environmental goals. It also provide data-driven insights that support sustainable decision-making. It helps maritime businesses, policymakers, and stakeholders make informed choices about technologies, materials, and fuels. This can drive the industry towards adopting green practices and investing in cleaner, more sustainable technologies.

Given this, it has rising voices that LCA should be considered an essential tool for the maritime industry as it could guide sustainable practices, ensures regulatory compliance, fosters innovation, and strengthens the industry's reputation in the context of environmental responsibility.

Nevertheless, the maritime industry faces great challenges on developing a standardized LCA model applicable for international shipping. Maritime activities involve various stakeholders, including shipbuilders, operators, and regulatory bodies. Coordinating efforts and ensuring collaboration among these stakeholders to collect necessary data and implement LCA practices uniformly can be a significant challenge.

In this context, the sub-sections delve into the primary challenges of developing a unified LCA model tailored to the shipping sector's policies.

1.1.1 Current issues on IMO LCA regulatory framework on marine fuels

In response, IMO has proposed an urgent workstream for developing *"life cycle GHG/carbon 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). Well-to-Wake (WtW) encompasses the entire life cycle of a fuel from production to combustion. Additionally, WtT refers to the emissions associated with the production and transportation of the fuel until it reaches the tank of the vessel, while TtW considers the emissions during the combustion of the fuel on the vessel. This is considered an meaningful step forward to addressing life cycle GHG impacts so that the shipping industry should be no longer misguided by the limitations of the current IMO instruments.

Key tasks of IMO’s guidelines are to develop robust default life cycle emission values for each marine fuel. These emission factors in these guidelines are likely to be collaborated as key inputs for enhancing the current IMO energy efficiency frameworks associated with EEDI, EEXI, CII and other instruments. Figure 1-2 shows credible scenarios - envisaged by this PhD research work - through which the scope of life cycle analysis on marine fuels can be proposed in multiple ways such as Well-to-Wake (WtW), Well-to-Tank, or Tank-to-Wake scopes.

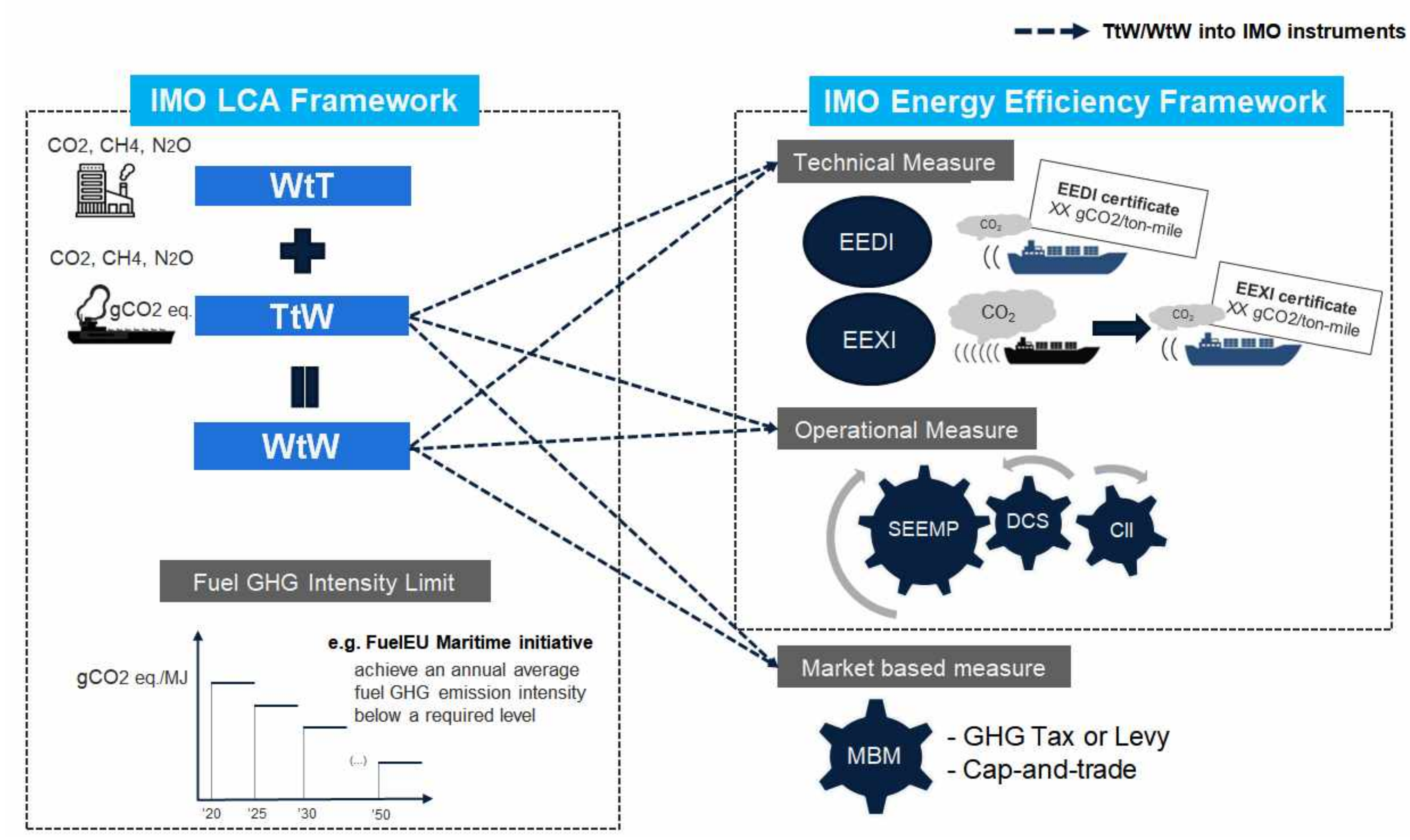


Figure 1-2. Overview of credible IMO LCA applications to existing regulatory frameworks (envisaged by the author).

Once default values are confirmed, the current IMO LCA framework is intent to introduce fuel certification schemes through a new guidance on verification and certification for actual GHG emissions from different marine fuels. It would offer, to some extent, flexibilities in industrial choices and options to incentivize the lower GHG emission fuels than the default values in the LCA guidelines. This approach is highly expected to allow fuel suppliers and ship operators to use actual emission values rather than default ones, whilst third-party verification and certification could also accommodate regional differences and specific feedstock.

However, LCA - methods, applications and practices - are still new in the marine sector. Such a brevity leads IMO encountered a series of challenges in a process of developing robust default emission values.

The absence of robust WtT and TtW emission default values would be a critical hinderance for developing a unified LCA methodology. Resultantly, it will cause a significant delay on the standardization of LCA as well as on the achievement of ‘net-zero’ in the marine sector.

For world fleets, robust default values for marine fuels should play a crucial role in understanding and setting-up proper levels of achievable targets onboard and in also incentivizing GHG reductions in life cycle footprint across the fuel supply chain. Under current status, it is more urgent to develop robust WtT and TtW emission values for conventional marine fuels rather than future fuels through a unified methodology.

Given that all the information on life cycle footprint is encapsulated into a single unit of robust default emission values, there has been several issues in determining those values in a proper manager. One challenge 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 life cycle 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 (2021) 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, 2021h). The identification and characterization of geographical differences in developing default emission factors for marine fuels is a crucial issue that needs to be addressed.

1.1.2 Challenges on developing an unified 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 life cycle GHG impacts of maritime fuels; not only limiting the GHG intensity driven from onboard fuel consumptions, but also using a life cycle 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 life cycle decarbonization by tracking fuel types, applied production methods, and supply chains of fuels from 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., 2023b). In this aspect, to assess the effectiveness of life cycle policies aimed at promoting cleaner energy sources, it is imperative to establish a baseline of life cycle 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.

Based on the background provided in Sections 1.1.1 and 1.1.2, this research aims to address some fundamental gaps in the current understanding of the LCA regulatory framework in the maritime sector.

Research questions

RQ 1 : What needs to be harmonized in the LCA regulatory framework for shipping sector?

RQ 2 : How should default GHG life cycle emission values for marine fuels be determined in import-dependent countries?

RQ 3 : And, to what extent do regional or geographic differences impact the GHG life cycle emission values of marine fuels, such as emissions from maritime transportation?

1.1.3 Issues on LCA methodologies in setting and evaluating the future WtW emission target

LCA approaches have gained prominence in recent years, particularly for comparing different existing and emerging technologies. Notably, their adoption has been widespread in the energy sector (Valente et al., 2021). Furthermore, these approaches are being leveraged to quantify impacts within complete energy systems. This is achieved by aggregating the impacts of the various technological processes inherent to these systems (Junne et al., 2020).

Shifting the focus to international shipping, regulations targeting GHG emissions typically involve two distinct stages. The first stage entails the establishment of a default or reference emission value, which serves as a cap on permissible emissions. This is followed by the definition of an enhanced regulatory value, pinpointed for a future date, taking into account anticipated technological advancements. The revised IMO Initial Strategy provides a roadmap for this, advocating a medium-term measure. Here, the carbon and GHG intensity of marine fuels is set to experience incremental reductions, aided by the introduction of GHG fuel standard (GFS) rooted in LCA.

In this context, there's a plethora of LCA methodologies to choose from, including Attributional LCA, Consequential LCA, Dynamic LCA and Prospective LCA etc. As international shipping ventures into the realms of policy-making, there's an imperative need to discern the most suitable LCA methodology. The chosen methodology should resonate with distinct objectives, whether that's the demarcation of the extant LCA emission baseline, the formulation of forward-looking emission criteria for impending GHG cutbacks, or envisioning the roadmap towards complete decarbonization by 2050. This latter objective becomes particularly salient in light of the emergence of sustainable alternative fuels.

Research questions:

RQ 4 : How can a comprehensive framework be developed to assess the extent to which the integration of these fuels might contribute to the attainment of

the GHG targets established for 2030, 2040, and 2050, as mandated by international shipping regulations?

RQ 5 : And how much can sustainable marine fuels reduce GHG emissions, particularly when compared to conventional fossil-based marine fuels?

1.1.4 Current challenge on accounting of GHG emissions from carbon neutral fuels and captured CO_2 in the shipping sector

Furthermore, at MEPC 80, Life Cycle Assessment (LCA) guidelines on marine fuel concerning marine fuel was adopted. These guidelines will enable the assessment of ships based on their WTW GHG intensity by utilizing factors developed under the guidelines in conjunction with fuel consumption data reported through the IMO's DCS. The IMO is also deliberating mid-term measures to be agreed upon and implemented between 2023 and 2030. One such proposed measure is the GHG Fuel Standard (GFS), which would impose limitations on the operational WTW GHG intensity of ships based on their reported fuel consumption within the DCS. The development of WtT and TtW GHG emission factors for current and future marine fuels and engines is underway as part of the IMO's aforementioned LCA guidelines.

However, it is noteworthy that the IMO currently lacks explicit guidance on the calculation and accounting of TtW CO_2 emissions for ships employing sustainable renewable fuels and onboard carbon capture system(OCCS). This gap persists despite ongoing developments in the LCA guidelines pertaining to marine fuel. Furthermore, the existing accounting principles outlined by the Intergovernmental Panel on Climate Change (IPCC) do not provide specific directives for addressing the use of sustainable renewable fuels and OCCS technology within the context of international shipping.

The use of carbon-based fuel with carbon neutrality such as biofuels and synthetic fuels is critical for decarbonizing the shipping industry. Under current regulatory framework, one of the main challenges is that the current accounting methods of the emissions from ship do not distinguish between emissions from carbon-neutral fuels namely sustainable renewable fuels and those from fossil fuels. As a result, emissions from sustainable renewable fuels may be overestimated, leading to an inaccurate representation of the actual carbon footprint of the shipping sector. This issue is further complicated by the lack of consistent accounting guidelines on CO_2 emissions from the shipping sector, which makes it difficult to develop effective policies to regulate carbon emissions from international shipping.

Another challenge in calculating CO_2 emissions from international shipping is the avoidance of double-counting emissions between the shipping industry and other sectors. For instance, if carbon captured from a ship is used in another sector as a feedstock for fuel production or conversions, it may be counted as a reduction in emissions in both sectors, resulting in an overestimation of the actual reduction in emissions. According to the IPCC guidelines state that any captured CO_2 for later uses should not be deducted in the sector where it is captured unless it is accounted for elsewhere in national GHG inventories. This could be understood that CO_2 captured onboard for later use or short-term storage should not be deducted from the CO_2 emissions from international shipping unless the CO_2 emissions are accounted for in the national GHG inventory.

To truly realize decarbonization within international shipping, it's imperative not only to disincentivize the extraction of more fossil fuels but also to champion carbon capture systems ensuring permanent carbon sequestration from sources.

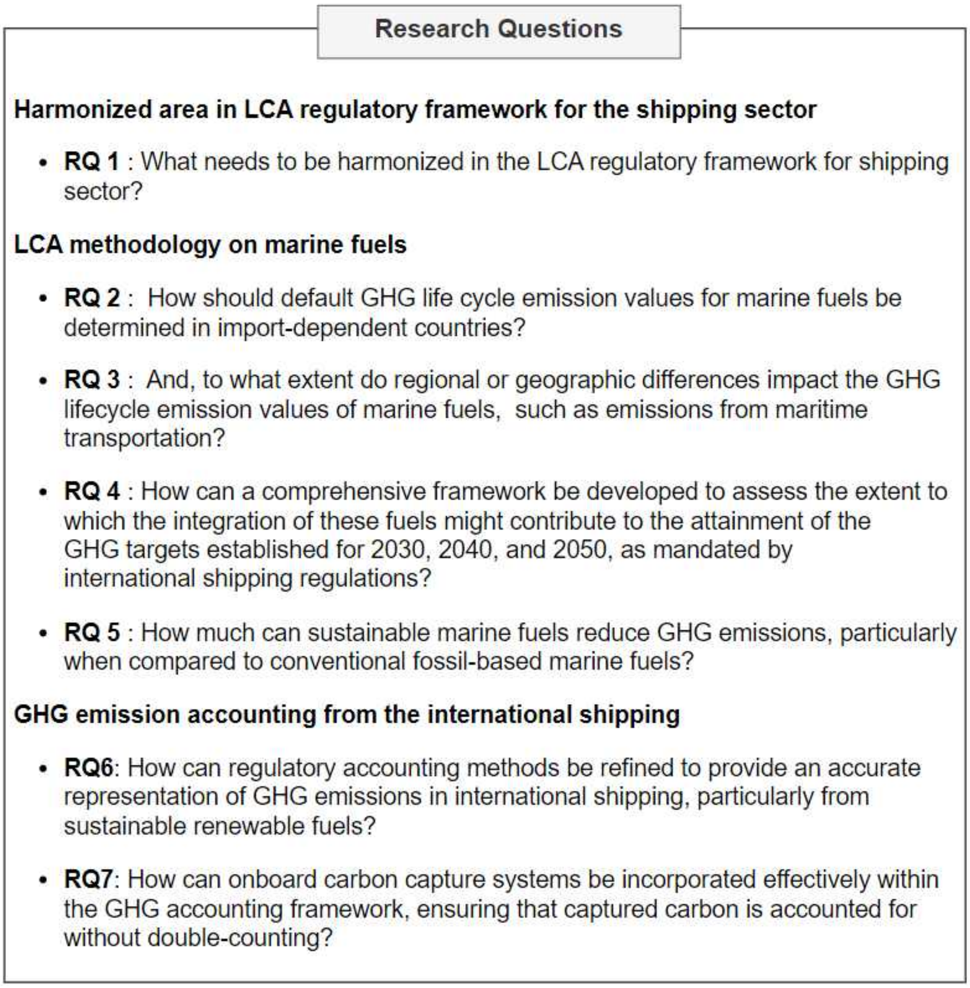
Research questions:

RQ6: How can regulatory accounting methods be refined to provide an accurate representation of GHG emissions in international shipping, particularly from sustainable renewable fuels?

RQ7: How can onboard carbon capture systems be incorporated effectively within the GHG accounting framework, ensuring that captured carbon is accounted for without double-counting?

1.2 Motivations

This thesis is driven by the following three principal concerns. These concerns arise from the complex challenges and essential questions detailed in sections 1.1.1 to 1.1.4 (refer to Figure 1-3):



Research Questions

Harmonized area in LCA regulatory framework for the shipping sector

- **RQ 1** : What needs to be harmonized in the LCA regulatory framework for shipping sector?

LCA methodology on marine fuels

- **RQ 2** : How should default GHG life cycle emission values for marine fuels be determined in import-dependent countries?
- **RQ 3** : And, to what extent do regional or geographic differences impact the GHG lifecycle emission values of marine fuels, such as emissions from maritime transportation?
- **RQ 4** : How can a comprehensive framework be developed to assess the extent to which the integration of these fuels might contribute to the attainment of the GHG targets established for 2030, 2040, and 2050, as mandated by international shipping regulations?
- **RQ 5** : How much can sustainable marine fuels reduce GHG emissions, particularly when compared to conventional fossil-based marine fuels?

GHG emission accounting from the international shipping

- **RQ6**: How can regulatory accounting methods be refined to provide an accurate representation of GHG emissions in international shipping, particularly from sustainable renewable fuels?
- **RQ7**: How can onboard carbon capture systems be incorporated effectively within the GHG accounting framework, ensuring that captured carbon is accounted for without double-counting?

Figure 1-3. Research questions addressed in this thesis

(a) The need for a harmonized LCA regulatory framework for the shipping sector

To respond to the escalating imperative for decarbonizing international shipping, the IMO has proposed the development of LCA guidelines for both present and prospective marine fuels. The objective is to facilitate the widespread adoption of cleaner fuels by encompassing not only the assessment of GHG life cycle emissions during the fuel utilization stage onboard but also during fuel production, storage, and transportation. Nevertheless, prevailing LCA practices within the shipping sector exhibit fragmentation and inconsistency, thereby posing the risk of potential gaps and discrepancies in GHG life cycle emission values. This thesis aims to bridge these gaps and establish a cohesive framework that is adaptable to the dynamic landscape of marine fuels and shipping operations (RQ1-RQ3).

(b) The need for a tailored LCA framework/methodology for the shipping industry

The diverse range of available LCA methodologies necessitates a tailored approach for the shipping industry that can establish an accurate emission baseline and pave the way for future GHG reduction milestones (RQ2-RQ5). This thesis seeks to develop such a methodology that meets the unique needs of the sector.

(c) The need for a comprehensive and standardized approach to GHG accounting

The lack of a comprehensive and standardized approach to GHG accounting, especially in the context of sustainable renewable fuels and carbon capture systems, is a pressing concern. The disparity in current accounting methods, coupled with potential pitfalls like double-counting, necessitates a rigorous research endeavor (RQ6-RQ7). This thesis seeks to shed light on these areas and offer pragmatic solutions that could recalibrate the industry's approach to GHG emission accounting.

In conclusion, this thesis is motivated by the imperative to address the critical challenges facing the shipping sector as it transitions to a more sustainable future. Through rigorous research and insightful analysis, this thesis aims to make a significant contribution to the development of effective policies, practices, and technologies that can support the sector's decarbonization pathway.

1.3 Outline of the thesis

To address the research questions, this thesis consists of 10 chapters and 3 appendices.

Chapter 2 introduces the research aim and objectives, along with an outline of the thesis to achieve them. **Chapter 3** reviews the application of Life Cycle Assessment (LCA) in policymaking across various transportation sectors, examining previous LCA studies on marine fuels to identify gaps and guiding the methodological development discussed in Chapter 4.

Chapter 4 conducts a detailed literature review to address the issues identified in Chapter 3. It reviews and analyses existing analysis methods within conventional life cycle assessment methodologies to identify research gaps and establish plans to address them.

Chapter 5 investigates areas requiring harmonization in the LCA regulatory framework, examining previous LCA studies on marine fuels, current regional policies, and approaches from other sectors.

Chapters 6 to 8 present case studies based on the newly proposed LCA framework for marine fuel. These chapters demonstrate the superiority and effectiveness of the new framework compared to conventional practices. Additionally, the case study results underscore the necessity of applying the new framework/methodologies to the shipping sector for decarbonization by 2050.

Chapter 9 discusses the contributions, novelties, limitations of this thesis, and provides recommendations for future research. Finally, **Chapter 10** summarizes and concludes the research.

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

- Appendix A contains supplementary material for the case study 'What Needs to be Harmonized in the LCA Regulatory Framework for Shipping Sector ?
- Appendix B contains supplementary material for the case study 'A Framework for Determining the Life Cycle GHG Emissions of Fossil Marine Fuels in Energy-Importing Countries via Maritime Transportation '
- Appendix C provides supplementary material for the case study 'A Prospective LCA Framework for Sustainable Renewable Fuels in International Shipping: Hydrogen-Based E-Fuels'

2 RESEARCH AIM AND OBJECTIVES

2.1 Aim and objectives

While sustainability assessments of marine fuels encompass various environmental impacts like acidification potential (AP) and eutrophication potential (EP), this study prioritizes Global Warming Potential (GWP) due to its critical role in climate change and the shipping sector's substantial contribution to GHG emissions. This focused approach facilitates a deeper understanding of the role of marine fuels in GHG reduction within the shipping context.

The primary aim of this thesis is to contribute to achieving net-zero GHG emissions in the shipping sector by proposing an advanced life cycle assessment policy framework concerning current and future marine fuels.

In order to achieve the aim, the following objectives should be accomplished:

- Objective 1: To identify gaps on policies on marine fuels for GHG reduction and on current LCA approaches/practices
- Objective 2: To develop an enhanced LCA framework tailored for achieving decarbonization goals suitable for the shipping sector.
- Objective 3: To demonstrate the adequacy of the proposed LCA framework through a series of case studies.
- Objective 4: To offer recommendations on the future LCA regulatory/political frameworks toward decarbonisation in the shipping sector at both local and global levels.

2.2 Outline of research and tasks

Figure 2-1 illustrates research approaches designed to achieve the aforementioned research aim and objectives. It also shows how the research questions (RQs) will be addressed across the tasks proposed below.

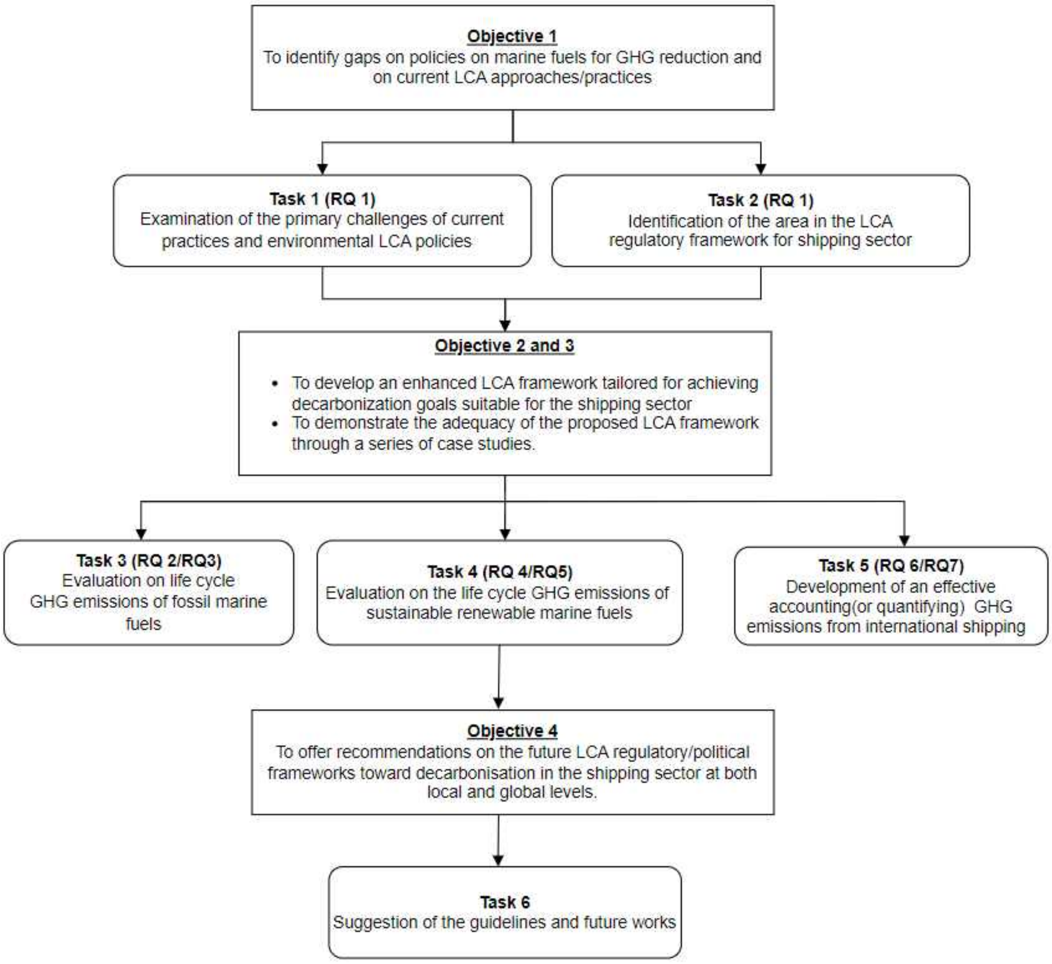


Figure 2-1. Outline flowchart for the research

Task 1 Examination of the primary challenges of current practices and environmental LCA policies

This task involved analyzing LCA policies from other transport sectors to bridge the gap between literature and existing policy practices. LCA-based approaches bolster policy-making and its implementation, serving as tools for policy evaluation.

Task 2 Identification of the area in the LCA regulatory framework for shipping sector

Building upon Task 1, this task aimed to systematically identify and assess potential areas for standardization and harmonization in the LCA regulatory framework for the shipping industry. The task focused on identifying and addressing the discrepancies and inconsistencies in current LCA practices to align them with the proposed guidelines by the IMO for marine fuels.

Task 3 Evaluation on life cycle GHG emissions of fossil marine fuels

This task aimed to evaluate the life cycle GHG emissions of conventional fossil marine fuels, focusing particularly on energy import-dependent countries. The primary goal was to assess the current life cycle GHG emissions of these fuels and the impact of geographic and regional differences on these emissions.

The task involved a detailed analysis of the life cycle emissions of conventional marine fuels produced and supplied in energy import-dependent countries, using South Korea as a case study.

Task 4 Evaluation on the life cycle GHG emissions of sustainable renewable marine fuels

Task 4 evaluated the life cycle GHG emissions of sustainable renewable marine fuels for international shipping, covering a comprehensive analysis of various production pathways. This involved a detailed assessment of the full life cycle of these fuels, from production to combustion in ships. The task also explored the potential role of these fuels as part of a broader shift to sustainable and renewable energy sources for marine fuel.

An enhanced prospective LCA framework was proposed to not only address the primary limitations of conventional LCA but also evaluate the potential contribution of sustainable renewable marine fuels towards meeting the GHG targets set for 2030, 2040, and 2050 by international shipping regulations.

Task 5 Development of an effective approach for accounting (or quantifying) GHG emissions from international shipping

Appropriate accounting methods were identified and suggested to precisely calculate GHG emissions in international shipping. The goal was to foster the uptake of sustainable renewable fuels and onboard carbon capture systems.

Task 6 Suggestion of the guidelines and future works

The findings from the PhD thesis were reviewed for overarching observations and insights. Their relevance to environmental guidelines and regulations was scrutinized. Moreover, the limitations of this study were highlighted, and directions for future research were proposed.

3 LITERATURE REVIEW

Given that this research aims to develop an advanced Life Cycle Assessment (LCA) policy framework for marine fuels, this chapter was designed to critically examine the current application of LCA from policy-making perspectives across various transport sectors while reviewing past LCA studies on marine fuels to identify gaps, thereby confirming the direction of methodological development in Ch. 4.

3.1 LCA application from policy-making perspectives across transport sectors

Before addressing previous LCA studies on marine fuel, this section described and analyzed LCA policies applied in other transport sectors to connect the literature to existing policy practices. LCA-based approaches support policy-making and its implementation, and can be used to evaluate policies (Lindstad and Rialland, 2020). Table 3-1 lists policy schemes in other transport sectors to which LCA has been applied.

Table 3-1. List of policy schemes featured by LCA approach in transport sectors excl. marine sector.

Scheme	Description	Fuels	Region	Scope
British Columbia Low Carbon Fuel Standard (BC-LCFS)	Requirements on annual goals for fuel suppliers to reduce the average carbon intensity of fossil fuels	Fossil fuels	British Columbia, Canada	WtW
California Low-Carbon Fuel Standard	Standard designed to reduce the carbon intensity of California's transportation fuel pool and promote the use of an variety of low-carbon and renewable alternatives fuel	Low-carbon and renewable alternatives fuel	US	WtW
Clean Fuel Standard	Standard for fuel suppliers (producers and importers) to reduce the life cycle carbon intensity of fuels	Fossil fuels	Canada	WtW
Renewable Energy Directive II (RED II)	Setting a common target for the promotion and use of energy from renewable sources within the EU	Biofuels and bioliquids	EU	WtW
Renewable Fuel Standard	Standard for fuel refiners or importers to achieve compliance by blending renewable fuels into transportation fuel(or by obtaining credits)	Renewable fuels including biofuels	US	WtW
Renewable Transport Fuel Obligation	Detailed regulation for biofuels used for transport and non-road mobile machinery	Biofuel	UK	WtT
ICAO CORSIA	Requirements on a CORSIA eligible fuel	Fossil fuels and renewable or waste-derived fuels	International aviation	WtW

Notable points from the LCA policy schemes are succinctly described as follows:

- Various regional and international regulations relate to fuels, including the California Low Carbon Fuel Standard, the UK Renewables Transport Fuels Obligation, the US Renewable Fuel Standard, the Washington Clean Fuel Standard, Renewable Energy Directive II (RED II), and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (Andreea Miu, 2021).

- Recognizing that the large amounts of biomass used to produce biofuels for replacing fossil fuels could lead to a significant increase in GHG emissions in the well-to-tank phase, as natural lands are converted to croplands (Searchinger et al., 2008), RED II adopted an LCA approach to avoid fuel production from biomass obtained from land with high carbon stock (Brandão et al., 2021). It provides a calculation method for attaining GHG emission reduction from biofuels and includes default values for a range of pathways.

- The International Civil Aviation Organization (ICAO) established CORSIA to help reduce aviation GHG emissions (ICAO, 2016). Under CORSIA, emissions reductions from the use of sustainable aviation fuels are calculated using an LCA approach, agreed upon at ICAO in 2018. The following four items are key elements amongst the agreed LCA method for CORSIA (ICAO, 2019b, ICAO, 2019a): accounting for GHG well-to-wake emissions, consideration of emissions from induced land use change (ILUC), safeguards against deforestation, and introduction of practices for low land use change (LUC). These elements encourage stakeholders to choose different options for sustainable aviation fuels to reduce life cycle CO_2 emissions while avoiding the risks of unforeseen consequences (Prussi et al., 2021).

These examples of policies investigated above should not be seen as flawless but are a starting point upon which the shipping sector can further harmonise with. From the perspective of marine fuels and shipping, the application of LCA in other transport sectors provides valuable insights for promoting environmental stewardship in maritime operations. These sectors illustrate how LCA can be used to inform and refine regulatory frameworks, effectively capturing the full environmental impact of fuel usage, from well-to-wake. Specifically, the comprehensive standards in aviation and automotive industries, which encompass carbon intensity benchmarks and land use change accounting, provide a model for the maritime sector to develop rigorous, transparent, and comprehensive criteria for pursuing a sustainable fuel transition. Moreover, the incorporation of default values and considerations of induced land use change, as seen in the RED II and ICAO CORSIA, can help the shipping industry quantify emissions reductions and establish safeguards to prevent unintended ecological impacts. By adopting similar LCA-based methodologies, the maritime sector can not only align with and contribute to the global tapestry of transport policies, but also establish a robust standard for environmental responsibility and fuel sustainability in one of the world's most pivotal industries. Further details are addressed in Chapter 5.

3.2 Past LCA studies on marine fuels and their gaps in approach

In undertaking the literature review, a systematic approach was employed to ensure a comprehensive exploration of relevant studies. The search strategy involved the utilization of prominent academic databases and search engines such as Scopus and Google Scholar. Boolean operators, including 'AND' and 'OR,' were strategically employed to refine the search and capture studies that intersect the keywords effectively.

For example, the primary keywords used for the literature search were 'marine fuel' and 'LCA' (Life Cycle Assessment). These keywords were selected with precision to target a broad yet relevant range of literature related to the environmental assessment of marine fuels. The search aimed to identify and review studies that significantly contribute to the understanding of life cycle assessment methodologies within the context of marine fuels.

The application of LCA within the shipping sector has evolved significantly over the past few decades, marking a pivotal shift in how environmental impacts are analyzed and addressed. Initially, institutions such as the Norwegian University of Science and Technology and the National Maritime Research Institute of Japan pioneered this integration by developing specialized LCA tools aimed at enhancing ship design for better energy efficiency and environmental impact (Kameyama et al., 2005, Ellingsen et al., 2002). These early efforts laid the foundation for comprehensive LCA methodologies, notably 'LIME' and the development of the LCA-ship software tool, designed to encompass the entire lifecycle of maritime vessels from construction to dismantling, thereby enabling a quantifiable analysis of their environmental footprint (Kameyama et al., 2007, Jivén et al., 2004, Nicolae et al., 2014).

Comparing LCA methodologies to existing regulatory frameworks reveals the broader applicability and depth of LCA in environmental efficiency within the maritime sector. The IMO still utilizes the EEDI and the EEOI which only focus on the user perspective for environmental performance. However, studies have demonstrated that LCA offers a more holistic assessment, capturing a wider range of emissions including CO2, NOx, and SOx, thus providing a more comprehensive environmental analysis throughout a vessel's lifecycle, from design to decommissioning (Blanco-Davis and Zhou, 2016). This comprehensive perspective afforded by LCA is crucial for the effective monitoring and reporting of maritime emissions, suggesting an enhancement over existing measures like EEDI and EEOI by delivering detailed environmental insights.

The evaluation of fuels and propulsion technologies through LCA has been central to identifying paths towards reducing the shipping industry's environmental impact. Research into the lifecycle impacts of various marine fuels (Hwang et al., 2019, Chen and Lam, 2022, Lindstad et al., 2021, Seddiek and Ammar, 2023, Spoof-Tuomi and Niemi, 2020, Lindstad and Rialland, 2020, Gilbert et al., 2018, Bilgili, 2021a, Perčić et al., 2020). Several studies comparing different fuel production pathways from renewable source and their life cycle environmental implications have been identified in the literature. (Perčić et al., 2020) assessed the viability of alternative fuels, including electricity, dimethyl ether, methanol, natural gas, hydrogen, and biodiesel, for their potential to mitigate CO_2 emissions within the short-sea shipping sector. Additionally, (Gilbert et al., 2018) conducted a life cycle assessment for a variety of fuels, including conventional and alternative options, and six emission types were investigated, hydrogen and synthetic fuels relying on decarbonizing production inputs, while biofuels were land-use change managed and sectoral. It was concluded that an improvement in competitiveness would have an effect. Furthermore, (Bilgili, 2021a) delved into evaluating the environmental impact throughout the life cycle of alternative marine fuels, such as biogas, dimethyl ether, ethanol, liquefied natural gas, liquefied petroleum gas, methanol, ammonia, and biodiesel. The goal was to address air pollution stemming from ship operations holistically. Their findings revealed that biogas emerged as the most promising fuel in both the short and long term, while methanol, ammonia, and biodiesel exhibited less favourable environmental performance. Furthermore, investigations into propulsion technologies, such as molten carbonate and solid oxide fuel cells, have identified these systems as environmentally superior to conventional diesel engines, further underscoring the importance of LCA in guiding the industry towards sustainable fuel choices and technologies (Alkaner and Zhou, 2006, Strazza et al., 2010).

In addition, 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 3-1.

3.2.1 LCA methodologies on marine fuels

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. However, several factors influence the broad range of outcomes in LCA studies of marine fuels. In particular, the use of LCA methodologies with significant uncertainties not only poses challenges in determining default emission values, but also creates uncertainty in the regulatory framework for marine fuels. This uncertainty can affect mid- and long-term measures for reducing GHG emissions and may hinder the effective uptake of low- and zero-carbon fuels in the shipping sector.

Although the global shipping industry is beginning to adopt a growing number of alternative fuels to transition away from fossil fuels (DNV, 2022), the scarcity of relevant studies with unified and harmonized LCA methodologies often leads stakeholders to disregard or underestimate the comprehensive impacts of eligible marine fuels on GHG emissions and sustainability aspects.

In the LCA modelling for default emission values, the selection of the attributional and consequential LCA (referred to as A-LCA and C-LCA) is a crucial element that greatly influences the 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 (Moretti et al., 2022b, Moretti et al., 2022a, Vázquez-Rowe et al., 2014, Chester and Cano, 2016, Earles and Halog, 2011).

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 (Zamagni et al., 2012, Brandão et al., 2014, Plevin et al., 2014, Hertwich, 2014, Dale and Kim, 2014, Schaubroeck et al., 2021, Ekvall, 2019, Prapaspongsa and Gheewala, 2017) 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, 2019b). Also, the LCA regulatory framework for marine fuels should clearly define the unified selection of A-LCA and C-LCA.

Besides C-LCA and A-LCA, an increasing amount of research is focusing on the LCA of novel, rising, or prospective technologies and product systems. The literature outlines diverse strategies and methods for undertaking forward-thinking LCA relevant to such evaluations(van der Giesen et al., 2020). For instance, Dynamic LCA aims to recognize the ever-changing nature of our world and acknowledges that future trajectories may diverge from initial expectations (Alfaro et al., 2010). On the other hand, Anticipatory LCA points out that traditional LCA often looks to the past and may not be adept at evaluating future trends; it further emphasizes the importance of engaging stakeholders to yield richer insights (Wender et al., 2014). When conducting a prospective LCA, one integrates analyses of an emerging technology in its nascent stage (e.g., small-scale production) while envisioning the technology in a later, advanced stage (e.g., large-scale production) (Arvidsson et al., 2014, Mendoza Beltran et al., 2020)

As highlighted by (Suh and Yang, 2014), no model is flawless; the key consideration is whether it offers meaningful insights based on the posed questions and available data. Some studies have employed the prospective LCA methodology to evaluate environmental performance at a future juncture when emerging technologies have reached a mature level in terms of their technical readiness (Ababneh and Hameed, 2022). In the literatures on marine fuels, (Kanchiralla et al., 2023) conducted a LCA examining various e-fuel production pathways in terms of their potential for climate impact reduction. This analysis encompassed three distinct vessel types: a RoPax ferry, a tanker, and a service vessel. (Korberg et al., 2021) conducted a comprehensive investigation into the viability of renewable fuels within diverse propulsion systems for forthcoming ships, aiming to replace fossil fuels by 2030. However, existing studies have been limited to a small number of vessels and have not accounted for the impact of GHG regulations on future emissions.

Table 3-2. Previous LCA studies on marine fuels

Author(s) and publication year	Type of Fuels	GHG emission Scope	Methodological choice	Geographical coverage for production	Maritime Transportation (International)
(Strazza et al., 2010)	Methanol, Bio-methanol, Liquified Natural Gas (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 more than 2.5%)
(Bengtsson et al., 2011)	Heavy Fuel Oil (HFO), Marine Gas Oil (MGO), LNG, Gas-to-Liquid (GTL)	CO_2, CH_4, and N_2O	Consequential	• Crude oil (HFO, MGO): European • LNG, GTL: North Sea	• HFO, MGO: ELCD database • LNG: 147K 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

Author(s) and publication year	Type of Fuels	GHG emission Scope	Methodological choice	Geographical coverage for production	Maritime Transportation (International)
(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:138K 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	• 147K LNG Carrier from Qatar/USA to Korea • 57K Tanker from Saudi Arabia/ USA to Korea
(Thinkstep, 2019)	HFO, Low Sulphur Fuel Oil (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	• HFO: pipeline to Rotterdam • LNG: Pipeline and LNG carrier

Author(s) and publication year	Type of Fuels	GHG emission Scope	Methodological choice	Geographical coverage for production	Maritime Transportation (International)
				• LNG: North sea and onshore Algeria	
(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, Liquefied Petroleum Gas (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) • Hydrgoen: Literature review	• Diesel oil: ELCD and Ecoinvent 3.6 database

Author(s) and publication year	Type of Fuels	GHG emission Scope	Methodological choice	Geographical coverage for production	Maritime Transportation (International)
(Seddiek and Ammar, 2023)	HFO, Ammonia	CO_2, CH_4, and N_2O	(no indication)	(no indication)	(no indication)

3.2.2 Life cycle emission values for marine fuels from a policy perspective

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 3-2, 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 28ravelled 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 less than 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 3-2. 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. Spoof-Tuomi and Niemi (2020), (Lindstad and Rialland, 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 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.

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.

On the other hand, the achievement of GHG reduction targets, as established by the IMO hinges on the decarbonization of marine fuels (Ampah et al., 2021). The integration of renewable fuels into the maritime industry holds significant potential for reducing GHG emissions (Svanberg et al., 2018). Specifically, the transition from fossil-based feedstock to renewable alternatives like biomass and renewable electricity becomes imperative for achieving net-zero emissions from shipping by 2050 (Department for Transport (UK), 2021). Within TtW accounting systems, ammonia and hydrogen are regarded as carbon zero or neutral. However, 'green' ammonia, hydrogen, and synthetic fuels are produced through energy-intensive processes, involving substantial material and water resource requirements (Valera-Medina and Banares-Alcantara, 2020, Olabi et al., 2023). Consequently, this might result in increased GHG emissions during the WtT stage. To address this concern, the shipping industry and policymakers have begun implementing the LCA framework within the shipping sector. One notable example is the development of life cycle GHG intensity guidelines for marine fuels (IMO, 2023a). In light of this, it is imperative to design maritime alternative fuel policies that effectively minimize the potential for unintended consequences that could compromise their climate and sustainability objectives. LCA plays a pivotal role not only in evaluating these risks and establishing safeguards but also in identifying the environmental impacts of products and services throughout their life cycle.

However, fewer studies examine whether the shipping sector can achieve the ambitious GHG reduction targets set by the IMO and policymakers. From a policy perspective, there has been a relatively limited emphasis on developing a comprehensive framework for evaluating the effectiveness of reduction strategies and meeting the goals of the IMO GHG Strategy, especially for introducing sustainable renewable fuels to international shipping.

3.2.3 LCA Challenges on sustainable renewable fuels in shipping sector and the carbon capture technology onboard

E-fuels produced from renewable resources, such as hydro, wind, or solar power, are viewed as a promising solution to reduce GHG emissions (de las Heras, 2022). Furthermore, e-fuels can act as a bridge for existing combustion technologies and fuel infrastructure to remain competitive in the transition to a low-carbon future, reducing greenhouse gas emissions and supporting environmental protection in sectors that are difficult to decarbonize immediately.

Synthetic fuels are typically produced artificially using hydrogen sourced from fossil fuels, such as natural gas, oil, and coal. Alternatively, they are referred to as ‘e-fuels’ when the hydrogen used is generated from renewable energy sources. Due to their properties closely resembling those of conventional fossil fuels, they can serve as ‘drop-in’ replacements for existing fossil fuels with minimal adjustments to current infrastructure and systems (Deutz et al., 2018). Despite containing hydrocarbons, e-fuels are manufactured using renewable electricity and environmentally friendly processes that directly capture carbon from the atmosphere, rendering them carbon-neutral. For instance, a study conducted by Matzen and Demirel (2016) explored methanol and dimethyl ether (DME) as alternative fuels derived from renewable hydrogen and carbon dioxide. Their analysis demonstrated that these alternative fuels reduced GHG emissions by 82-86% compared to conventional fossil fuels. Similarly Lindstad et al. (2021) found that e-diesel and e-methanol exhibited the highest GHG reduction ratio, at 99%, among synthetic fuels. Another category of e-fuels, applied in marine transportation, includes e-hydrogen and e-ammonia, produced by electrolyzing water using electricity generated from renewable energy sources. These fuels are entirely carbon-free because they lack carbon content (Yan et al., 2023).

From the research conducted by Chen and Lam (2022), it was found that switching a ship's fuel to hydrogen, which does not generate GHG during operation, can result in a reduction of approximately 85% in GWP. Additionally, in the study described by Yan et al. (2023), e-ammonia demonstrated a reduction of 94% in GHG emissions and e-hydrogen demonstrated a complete elimination of such emissions.

For synthetic fuels and E-fuels, the production stage of the fuel is critical in addition to simply reducing emissions through fuel conversion. Research in (Brynolf et al., 2014) confirmed that methanol produced with natural gas has a higher GWP than bio-methanol, and there was no significant difference from Heavy Fuel Oil (HFO). Additionally, the study of Winebrake et al. (2019) proved that methanol produced using natural gas had a higher GHG value than Marine Diesel Oil (MDO). According to Abejón et al. (2020), the environmental performance of hydrogen depends on the primary source (fossil fuel or renewable energy) and the production process. Fernández-Ríos et al. (2022) confirmed a GHG reduction effect of more than 90% depending on the hydrogen production method. However, the environmental assessment indicates that under certain conditions, a Proton Exchange Membrane Fuel Cell (PEMFC) powered by hydrogen produced via Steam Methane Reforming (SMR) can generate more GHG emissions than a conventional fossil fuel-powered Internal Combustion Engine (ICE). Furthermore, even if the same hydrogen is used, ICE generates less GHG than PEMFC from a life cycle perspective, suggesting that ICE is a more suitable alternative in the long term. By Perčić et al. (2020), the environmental impact of hydrogen and ammonia produced by natural gas was evaluated, and higher GHG emissions than Diesel were confirmed. From Zincir (2022), the amount of CO_2 emissions, which varies widely depending on the source used in ammonia production, was confirmed. It was found that when ammonia is produced using fossil fuels, up to about 2.5 times more CO_2 can be emitted than when MDO production and use. In addition, the study in Lindstad et al. (2021) presented that in the case of ammonia and hydrogen, which are considered eco-friendly fuels, when produced using natural gas, 40% and 66% more GHG emissions than MGO, respectively, are generated. These findings emphasize the importance of the fuel production method to achieve environmental improvement in the sector.

Furthermore, studies aimed at reducing GHG emissions throughout the life cycle of these fuels through carbon capture systems (CCS) have been published. Matzen et al. (2015) conducted an environmental impact assessment for two hydrogenation processes that produce renewable methanol and ammonia, utilizing wind-power-based electrolytic hydrogen. Methanol production involves using CO2 from an ethanol plant, while ammonia production relies on nitrogen supplied by an Air Separation Unit (ASU). Gilbert et al. (2018) provided options to reduce emissions from ships by considering various fuels such as HFO, MDO, LNG, hydrogen, methanol, bio-LNG, bio-diesel, and Straight vegetable oil (SVO). In particular, in the case of hydrogen, grey hydrogen produced using LNG, blue hydrogen using CCS during production, and green hydrogen using renewable energy were compared. This study provides a direction for the decarbonization of the shipping sector by specifying the GHG value that varies depending on the energy source and CCS input in the production stage through evaluation considered from the fuel production stage. In addition to these studies, synthetic fuels are continuously being studied and reviewed based on discussions on the policy part of e-fuels, presenting future policy directions as in Skov and Schneider (2022).

However, despite these spectacular advantages, these fuels have the disadvantages of high energy requirements and significant costs with current technology (Fasihi et al., 2019, Xing et al., 2020), as well as a tight production infrastructure (Skov and Schneider, 2022). Although the IMO has announced a long-term strategy to phase out the GHG emissions from shipping, OCCS technology are still in their infancy unlike the onshore fixed CCS facilities (Ji et al., 2021). CCS for shipping application has focused on enhancement of CO_2 capture rate.

Research to utilize CCS for ships has also been actively conducted. For example, Zhou and Wang (2014) proposed a new chemical carbon dioxide absorption and solidification method for onboard carbon dioxide storage and conducted feasibility and cost evaluations applied to case ships.

In the late 2010s, as the scope of research expanded not only to the technical aspects of CCS but also to the economic aspects, Luo and Wang (2017) conducted a techno-economic evaluation under the assumption that CCS was used in a general cargo ship to determine the cost of various options. Fang et al. (2019) proposed an optimal sizing method to determine the capacity of shipboard CCS under strict EEOI constraints. Wang et al. (2017) conducted a feasibility assessment of the current policy review for EEDI, EEOI, and CCS and provided guidance for the application and practical installation of CCS systems on ships. Feenstra et al. (2019) conducted a techno-economic evaluation of ship-based carbon capture (SBCC) and revealed that SBCC could be more effective on large LNG ships.

In addition, Lee et al. (2021) proposed a new EEDI calculation method considering the onboard carbon capture and storage (OCCS) system, demonstrating that OCCS can achieve a higher capture rate than the actual EEDI reduction rate. Ji et al. (2021) integrated ship engine process modelling and chemical adsorption/desorption process modelling techniques to find the most efficient and sustainable post-combustion carbon capture (PCC) solution for LNG tankers, proposing a capture propulsion tank system and demonstrating that mixed amines are the optimal solvent to meet the requirements of the IMO carbon reduction strategy.

Overall, in terms of mitigating carbon emissions generated by shipping, carbon capture technologies have emerged as a promising solution. However, several challenges still hinder the practical implementation of these technologies on ships. Among these challenges are the need to minimize energy consumption, infrastructure demands, and to address issues such as corrosion, contamination, and maintenance. Consequently, there is a pressing need for continuous research and development to refine carbon capture technology for use in marine vessels and to effectively surmount the obstacles unique to this context. In contrast to the extensive research conducted on carbon capture in onshore facilities, the field of maritime or onboard carbon capture is still in its nascent stages of development (Ji et al., 2021). Previous research has assessed the efficacy of OCCS by examining simulation outcomes, capture rates, and associated costs (Ji et al., 2021, Feenstra et al., 2019, Voice and Hamad, 2022, Ros et al., 2022, Awoyomi et al., 2019, Luo and Wang, 2017).

Nonetheless, a literature gap persists with regard to accounting of the reduction of CO_2 resulting from the captured carbon source in a regulatory context. Additionally, the impact of OCCS installation on ships' carbon intensity indicator (CII), remains largely unexplored.

3.3 Research gap identification

The marine sector is a significant contributor to GHG emissions, prompting an increased interest in sustainable marine transportation solutions. Yet, research gaps notably persist in understanding life cycle GHG emissions from marine fuels. These gaps impede the formation of effective policies and practical strategies aimed at curbing marine emissions.

Through the critical review on the past/current LCA practices in the marine sector, the following three key research gaps were identified so that to be addressed through this research :

(a) Lack of reliable default life cycle emission values for marine fuels

Policymakers need access to reliable data on GHG emissions from marine fuels in order to develop effective policies for promoting sustainable and renewable fuels in the shipping sector. However, there is a lack of clear guidance or practice for establishing a baseline of life cycle GHG emission values, particularly in countries that rely on energy imports. To enhance the accuracy of default GHG emission values for marine fuels, unified methodological criteria, such as the scope of GHG emissions, global warming potential, functional unit, and inventory database, should be applied when developing these values. This study will develop reliable default WtW emission values of marine fuels and establish a database tailored to specific countries and circumstances.

(b) Lack of a comprehensive framework for evaluating the efficacy of reduction strategies and achieving the outlined targets in the IMO GHG Strategy

The IMO GHG Strategy sets ambitious targets for reducing GHG emissions from international shipping. However, there is no clear framework for evaluating the efficacy of reduction strategies and achieving these targets. This study will develop a comprehensive framework for evaluating the life cycle GHG impact assessment framework for various decarbonization choices for shipping industries under different fuel uptake scenarios. This framework will consider factors such as projected transport demand, scrapping rates, and the influence of regulatory measures.

(c) Challenges on Accounting of GHG Emissions for Sustainable Fuels and OCCS

Numerous studies have explored the life cycle GHG emissions of sustainable renewable fuels and the efficiency of onboard carbon capture systems (OCCS). Still, clear guidance or best practices for accounting for these emissions in international shipping remains elusive. This research proposes a unified accounting methodology to bolster the LCA frameworks of both national and regional regulations. The approach considers the carbon source and the destination of the captured carbon onboard.

4 METHODOLOGY

The previous chapter introduced the application of LCA for policy in various transport sectors, highlighted current research trends, and identified existing research gaps. Consequently, this chapter proposes an enhanced LCA approach that aims to address these challenges. This approach is specifically designed to navigate the complexities of GHG emissions from marine fuels and to facilitate the transition towards more sustainable shipping practices, as depicted in Figure 4-1.

The figure elucidates the research methodology, not only indicating relations between chapters but also offering insights into the systematic framework adopted to achieve the study's objectives. The approach is organized into three overarching sections: (1) System boundary and modelling, (2) Emission assessment, and (3) Generalization for policy making.

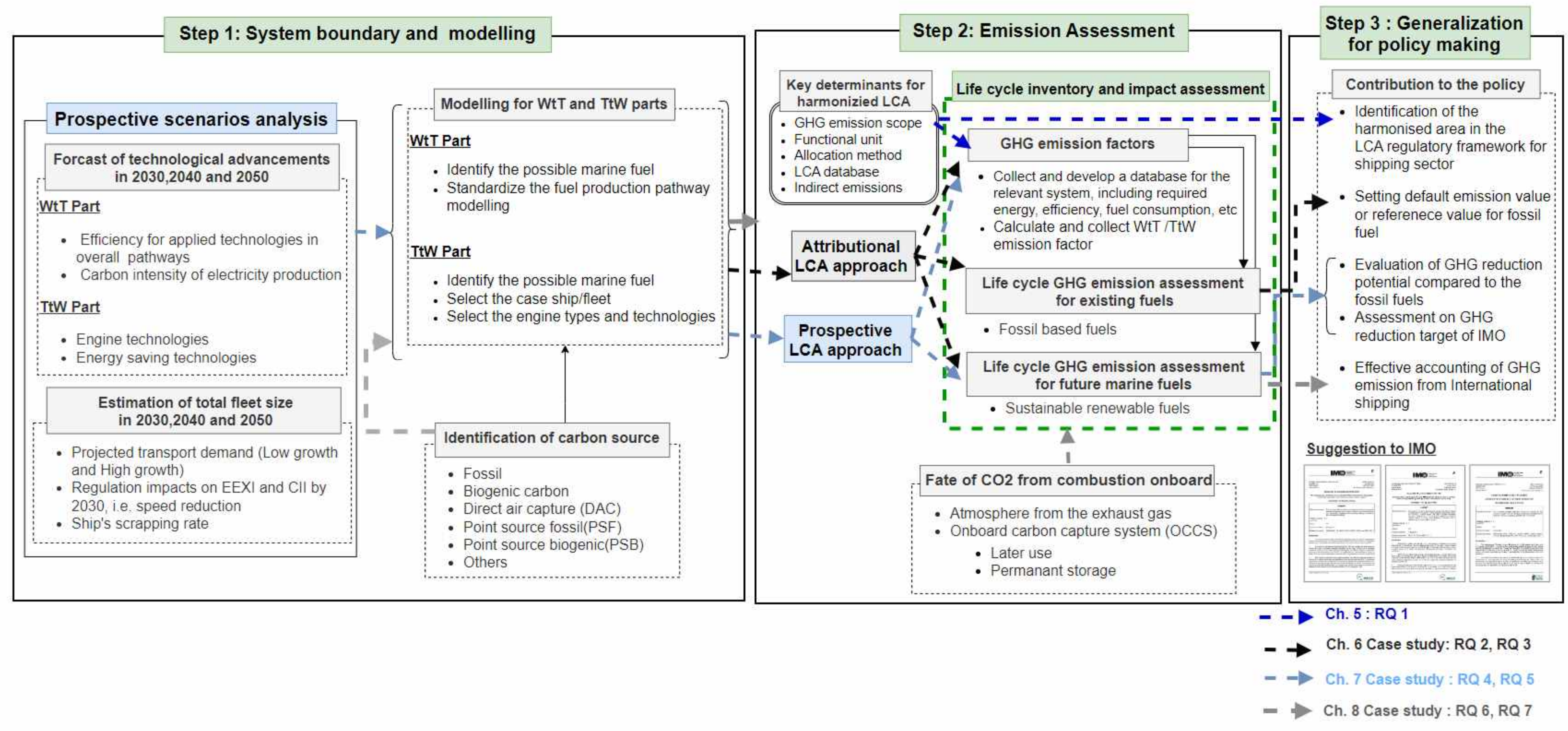


Figure 4-1. Enhanced LCA Methodologies for marine fuels policy framework: A study flowchart

4.1 System Boundary and Modelling

The initial phase focuses on defining the system boundary and establishing a robust modelling framework. It involves a comprehensive goal and scope definition as outlined in the ISO 14040 and 14044, clarifying evaluation objectives, functional units, system boundaries, activities included or excluded, and environmental impacts. This phase addresses key issues, such as the purpose of the LCA, the target group, and the specific decisions it aims to inform. By clearly delineating these parameters, the research maintains a focused and relevant scope.

4.1.1 Modelling for WtT and TtW parts

In the WtT modelling phase, potential marine fuels are identified and prioritized based on feasibility and environmental impact. Structured models of fuel production pathways are developed to analyze various stages and checkpoints.

The TtW modelling phase involves selecting a representative ship or fleet to simulate real-world feasible scenarios. An extensive evaluation of engine types and technologies is conducted to determine the most suitable configurations.

4.1.2 Prospective scenarios analysis

The analysis of the prospective scenarios is key elements of implementing prospective LCA to evaluate environmental performance at a future juncture when emerging technologies have reached a mature level in terms of their technical readiness. This study is considered following technological advancements and total fleet size considering these elements have influences on future life cycle GHG emissions on marine fuels.

(a) Forecast of technological advancements in 2030,2040 and 2050

This phase of the study involves forecasting technological advancements of Estimated potential improvement for current and future technologies for the years 2030, 2040, and 2050. The analysis is segmented into two parts:

WtT part focuses on the efficiency of applied technologies in overall pathways and the carbon intensity of electricity production. TtW part focuses on the evolving engine technologies and innovations in energy-saving technologies.

(b) Estimation of total fleet size in 2030,2040 and 2050

In addition to the technological advancements, the analysis of estimated total fleet size also considers the following factors: 1) Projected transport demand (considering both low growth and high growth scenarios), 2) Regulation impacts, particularly on the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) by 2030, 3) the ship's scrapping rate

4.1.3 Identification of carbon source

Identifying the origin of the carbon contained in a fuel is crucial to evaluating its life cycle carbon neutrality and sustainability. In this study, 'carbon source' refers to the carbon origin of the feedstock used to produce marine fuels. This can include various sources, such as fossil carbon, biogenic carbon, captured carbon from direct air capture (DAC), captured carbon from point source fossil fuels (PSF), captured carbon from point source biogenic sources (PSB), and mixed sources. The identification of the carbon source is prioritized to enable accounting of GHG emissions from the international shipping sector while avoiding double counting across sectors.

4.2 Emission Assessment

This emission assessment includes life cycle inventory (LCI) generation in line with ISO 14044. The LCI process involves: (a) Preparing for data collection based on the goal and scope; (b) Collecting data; (c) Allocating data (if necessary); (d) Associating data with unit processes; (e) Associating data with functional units; (f) Aggregating data.

A comprehensive database is compiled for the WtT part, covering relevant systems, such as required energy or system efficiency, during feedstock production, conversion to fuel, and distribution, including transportation. This also includes emission factors. For the TtW part, fuel consumption is calculated for the chosen fuels and engines to quantify efficiency and performance, providing a foundation for environmental impact assessments.

As the next step, this emission assessment, as part of a life cycle impact assessment (LCIA), evaluates the potential impacts of elementary flows identified in the WtT and TtW stages for allocating and calculating GHG emissions. According to the ISO 14040 and 14044 standards, impact categories typically include global warming, ozone depletion, acidification, human toxicity, among others (Chordia et al., 2021). This study focuses primarily on the global warming potential (GWP), using carbon dioxide equivalent (CO2eq) to characterize the GWP of different GHGs.

In assessing GHG emissions, the study employs an attributional LCA to quantify and accumulate emissions from both current and future marine fuels. These fuels include fossil-based and sustainable renewable options. A prospective LCA framework/methodology is used to evaluate life cycle GHG emissions of future marine fuels. This involves considering technological advancements in WtT and TtW processes and estimating fleet sizes for 2030, 2040, and 2050. Additionally, key factors for a unified and harmonized LCA are identified to enhance the implementation of a rigorous LCA policy for marine fuels.

Understanding the fate of CO_2 post-combustion is crucial. This includes examining the trajectory of CO_2 after combustion, whether it is released into the atmosphere or sequestered onboard. CO_2 emissions from ship combustion are instantaneous. However, achieving zero CO_2 emissions in the long term is possible for vessels equipped with onboard carbon capture and storage systems (OCCS). Methods enabling this include carbon capture and storage (CCS), leading to permanent sequestration, solid carbon capture, and perpetual carbon capture integrated with fuel usage cycles.

4.3 Generalization for Policy Making

This step is a crucial stage in which the findings and methodologies developed in previous sections are translated into broader policy recommendations, for instance, through submissions to the International Maritime Organization (IMO).

Identifying areas to be harmonised within LCA regulatory framework that can be standardized across the shipping sector is the focus of the first research question (RQ1), as illustrated in Figure 4-1 and explored in depth in Chapter **5**.

The establishment of benchmark or reference values for the greenhouse gas (GHG) emissions of fossil fuels, contributing to the "Setting default emission values for fossil fuels," is addressed in research questions **RQ2** and **RQ3**, with a detailed case study presented in **Chapter 6**.

Research questions **RQ4** and **RQ5** delve into not only the "Evaluation of GHG reduction potential compared to fossil fuels" but also the "Assessment of GHG Reduction Targets of the IMO," with insights drawn from a case study in **Chapter 7**.

Lastly, the contribution to "Effective accounting of GHG emissions from international shipping" is the subject of research questions **RQ6** and **RQ7**, and this is elucidated through a case study included in **Chapter 8**.

5 WHAT NEEDS TO BE HARMONIZED IN THE LCA REGULATORY FRAMEWORK FOR SHIPPING SECTOR ?

5.1 Introduction

To address the growing pressure to decarbonize international shipping, the IMO has proposed to develop LCA guidelines for current and future marine fuels in order to promote the adoption of cleaner fuels. This study aims to identify areas for harmonization in the LCA regulatory framework for marine fuels by examining previous LCA studies, currently available regional policies, and approaches from other sectors. Previous studies have extensively used LCA to investigate alternative marine fuels, primarily comparing and contrasting them with conventional fossil fuels. However, several factors contribute to the wide range of outcomes in LCA studies of marine fuels, such as differences in methodological criteria such as the scope of GHG emissions, global warming potential, sustainability criteria, functional unit, and inventory database. Notable points from these studies are further elaborated as follows.

5.2 Determinants for a Unified LCA Framework in the Shipping Sector

5.2.1 GHG emissions scope

The United Nations Framework Convention on Climate Change (UNFCCC) identifies six greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6) (UNFCCC, 2020). However, existing IMO instruments such as EEDI, EEXI, AER, and EEOI only address CO_2 emissions among all the GHGs defined by the UNFCCC and the Intergovernmental Panel on Climate Change (IPCC). The Fourth IMO GHG Study estimated the emissions of not only CO_2, CH_4, and N_2O but also black carbon (BC) with a high global warming potential (GWP) from the shipping sector (IMO, 2020).

Most studies(see Table A-1) investgated in this reserach do not consider BC when LCA on marine fuels while some IMO documents regarding voluntary ship BC projects have been published in recent years in order to evaluate BC impact on global wariming (Aakko-Saksa et al., 2023). It is worth noting that after CO_2 emissions, non-gaseous BC emissions are the second most important anthropogenic greenhouse gas contributing to global warming, with a Global Warming Potential (GWP) of 900 (Olmer et al., 2017). A study argued that including BC emissions would increase shipping's CO_2 equivalent emissions by approximately 7% from 3% (Friedlingstein et al., 2019, Friedlingstein et al., 2020). The warming impacts of BC emissions are significant, especially in the Arctic, where they are trapped in ice, since BC is dark in color and strongly absorbs light, which warms the atmosphere as light energy is converted to heat(Andreae and Gelencsér, 2006). The IMO has adopted a resolution encouraging the voluntary use of environmental fuels in the Arctic to reduce BC emissions (IMO, 2021g). However, there is currently no concrete regulation regarding the measurement of black carbon in the IMO or its GWP.

Also, including BC in the LCA framework would introduce substantial complexity, making it difficult to implement. Therefore, it may be more appropriate to address BC through other types of regulation at this stage. For the purpose of life cycle GHG emissions in the IMO LCA framework, the GHGs included should be limited to CO_2, CH_4, and N_2O, as these gases represent the majority of GHGs emitted in transportation sectors. Nevertheless, future research should continue to explore the inclusion of BC in the LCA framework as understanding its impact is crucial for reducing the shipping industry's contribution to global warming.

5.2.2 Global warming potential

Global Warming Potential (GWP) is a measure of each GHG's ability to trap heat in the atmosphere over a specific time period, compared to each ton of CO_2 emissions(UNFCCC, 2020). Legislative acts in the transport sector, as shown in Table A-1, such as EU RED II and CORSIA, typically consider GWP over a 100-year timeframe (Capaz et al., 2021). It is worth noting that the studies reviewed in Table A-1commonly adopt the default GWP values over 100 years as a standard practice.

Nevertheless, some studies present results using the 20-year time frame for sensitivity analysis purposes, underscoring the significance of taking into account GWPs over 20 years (Winebrake et al., 2019, Pavlenko et al., 2020, Comer and Osipova, 2021, El-Houjeiri et al., 2019). In the context of policymaking by IMO, some experts have argued that mitigating GHG emissions with high 20-year GWP, such as methane and BC, can contribute to avoiding additional near-term warming, which is crucial for achieving the global temperature goal of the Paris Agreement (Comer and Osipova, 2021). Although the Intergovernmental Panel on Climate Change (IPCC) reports publish GWPs over 20, 100, and 500-year time horizons, the regulations referred to have adopted GWP100 values (Guo and Murphy, 2012, Forster et al., 2021).

When calculating carbon dioxide equivalent emissions (CO2eq) as the sum of the three GHGs mentioned earlier, the use of updated GWP100 values for CH_4 (29.8) and N_2O (273) from the IPCC's Sixth Assessment Report (AR6) should be recommended over the GWP100 multipliers from the AR5, which have been widely used in previous studies investigated. The IPCC periodically compiles and revises GWP estimates, making it necessary to use the latest values to align IMO policies with the UNFCCC and other internationally recognized reporting standards for GHG emissions. Therefore, to enable comparative assessments with other sectors, it is important to consider GWP over 100 years.

5.2.3 Functional unit

Life cycle assessment (LCA) is a methodology that assesses the environmental impacts of a product or process system with regards to its function, such as GWP or acidification impacts per kilogram (kg) of product (ISO, 2006). The functional unit, as a reference, plays a crucial role in comparing LCA results and quantifying the performance of a product. In comparing many LCA studies ofproducts in terms of their environmental performances or impacts, the functional unit ensures the comparison of the evaluated fuels and their technologies (DeMarco and Fortier, 2022, McAuliffe et al., 2020).

However, the application of different functional units for identical fuels and technologies may entangle comparisons between results or makes them incomparable (Artz et al., 2018). Thus, it is crucial to prioritize defining an acceptable functional unit to improve comparability among studies. Defining the functional unit is a crucial step that is carried out in conjunction with determining the goal and scope of the assessment at the initial stage of any LCA (ISO, 2006). For policymakers who are in the process of developing an LCA regulatory framework, clear and precise definition of the functional unit is critical. It is significant to observe that other transport sectors that have adopted an LCA approach, as indicated in the Section 3.1, have normalized the basis of gCO_2eq/MJ of fuel.

For the WtT part of marine fuel, the global warming impact for the marine fuels can be fairly compared based on per MJ of delivered energy. On the other hand, in considering TtW part, an appropriate functional unit should carefully be chosen. Based on previous LCA research on marine fuels (refer to Table A-1), the functional units for LCA can be classified as shown in Table 5-1 and Table A-1.

Table 5-1. Possible functional units for IMO LCA Frameworks

Option	Functional Unit	Purpose

1	$gCO_2eq/MJ_{shaft\ work}$ or $gCO_2eq/kWh_{engine\ output}$.	This unit can rank order or prioritise specific propulsion systems with specific fuel
2	$t\ CO_2eq/tonne\text{-}nm$	This unit with transport work (tonne-nm) can rank order or evaluate the performance of specific vessels or operators
3	tCO_2eq/t_{fuel} or $gCO_2eq/\ MJ_{LHV,fuel}$	This unit is multiplied by fuel quantities to evaluate total life cycle emissions

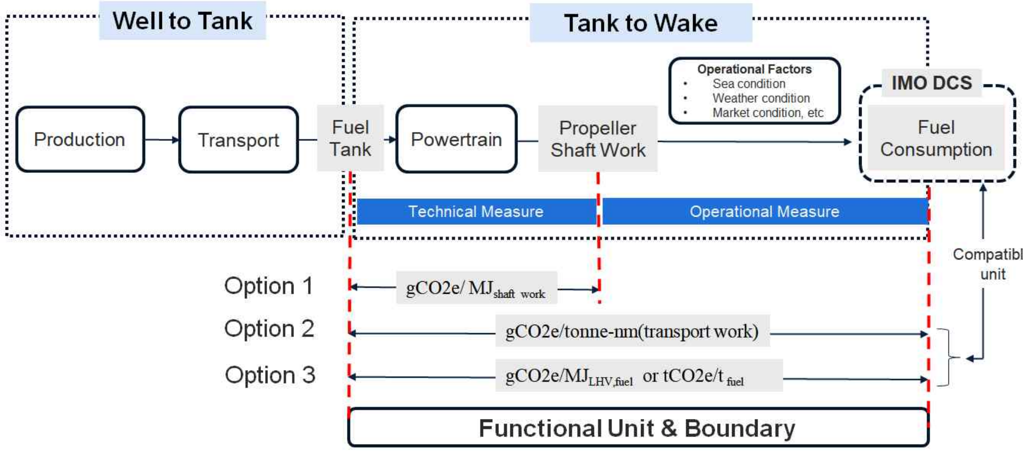


Figure 5-1. Diagram of possible functional units for IMO LCA Frameworks

Several studies have utilized the functional unit of $gCO_2eq/MJ_{shaft\ work}$ or $gCO_2eq/kWh_{engine\ output}$ for analyzing WtW and TtW GHG emissions. However, this functional unit only accounts for the efficiency and emission from engine and does not consider the specific characteristics of the vessel or operational factors, as illustrated in Table A-1. As an alternative functional unit, the carbon intensity of ships or the shipping sector, expressed as gCO_2eq/tonne-nautical mile, represents CO_2 emissions per transport work and correlates emissions to the amount of cargo transported and the distance sailed by a particular vessel (IMO, 2022e). This functional unit facilitates the evaluation of individual vessel performance through a unified approach that enables the use of all available technologies to reduce emissions. Nevertheless, the effectiveness of this unit relies on understanding the vessels being compared and accounting for operational factors that affect GHG emissions (Sharafian et al., 2019, Laugen, 2013, Ashrafi et al., 2022). It should be noted that this functional unit cannot accomplish the objective of calculating the GHG/carbon intensity of marine fuels.

The IMO LCA regulatory framework under discussion aims to account for GHG/carbon emissions from ships/international shipping, and regulatory regimes based on accounting emissions from international shipping should follow the principles set out in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories(IMO, 2021h). A functional unit of gCO_2eq/g_{fuel} multiplied by fuel quantities consumed, using data from the IMO DCS, provides a means of accounting for life cycle emissions. The standard lower heating value for the specific fuel can be used to convert fuel consumption reported in tons to MJ.

While a functional unit of gCO_2eq/g_{fuel} or $gCO_2eq/MJ_{LHV,fuel}$ is commonly used for comparing the life cycle emissions of fuels, it may not be sufficient for directly comparing diverse energy converters that differ in type, strokes, speed, pressure, or cycle. In addition, this approach may not account for emissions differently from fuels such as LNG Diesel, Lean Burn Spark Ignited (LBSI) engines, steam and gas turbines, and fuel cells (IMO, 2022c). Therefore, it is recommended that TtW emission factors be developed and applied differently depending on the type of energy converter. However, fuel consumption reported to the IMO DCS can capture the propulsion system efficiency, vessel efficiency, and the impact of operational factors. Thus, the use of gCO_2eq/g_{fuel} or $gCO_2eq/MJ_{LHV,fuel}$ as units for calculating WtW emissions based on fuel consumption is appropriate and aligned with EU and IMO policies.

5.2.4 LCA database / modelling tool

The different LCA databases/tools were identified among the analysed studies focusing on marine fuels, as shown in Table A-1. In particular, the Ecoinvent, the European Reference Life Cycle Database (ELCD), GREET, Gabi and SimaPro were mainly taken into account. One of the main reasons for the significant differences observed among LCA studies is the selection of the LCA database. Therefore, it is crucial to have a clear understanding of the database and reference sources while selecting relevant emission data to quantify and improve uncertainty.

(a) Ecoinvent

Ecoinvent, established through collaboration between the ETH Domain and the Swiss Federal Office, is known for its reliance on industry-established averages. Integrated into prominent software platforms like SimaPro, GaBi, and Umberto, it is recognized for its consistency and transparency (Martínez-Rocamora et al., 2016). Ecoinvent datasets provide comprehensive details on industrial or agricultural processes, including resource extraction, emissions, and the production and use of interconnected products(Weidema et al., 2013).

(b) ELCD database

The European Life Cycle Database (ELCD) was developed under the European Platform on Life Cycle Assessment, part of the Joint Research Centre of the European Commission. Launched in 2006, its goal is to provide LCA data specific to the European market (Fazio et al., 2015) . Freely accessible, it is included in software like SimaPro and GaBi and aims to complement other data sources in the International Reference Life Cycle Data System (ILCD) Data Network (Martínez-Rocamora et al., 2016)

(c) GaBi Database

GaBi, developed by PE Product Engineering GmBH and IKP in Germany, is a comprehensive LCA software that goes beyond data provision to facilitate LCA analyses. Accessible through Thinkstep, it integrates various databases including its own, Ecoinvent, and datasets from the US, Switzerland, etc. (Olagunju and Olanrewaju, 2020, Wernet et al., 2016, Lai et al., 2022)

(d) GREET

GREET, primarily focused on North American transportation fuels, including alternative marine fuels, offers a robust platform for evaluating emissions. It examines parameters like cumulative energy consumption, GHG emissions, and the release of major pollutants such as VOCs, CO, NOx, PM2.5, PM10, and SOx(De Kleine et al., 2014, Lai et al., 2022)

(e) SimaPro

Developed by PRé Consultants, SimaPro has been a key player in LCA tools for over 25 years, used in more than 80 countries. Continuously updated, it integrates datasets from sources like Ecoinvent, ELCD, and industry data, with clear attribution for each dataset's origin (Hollerud et al., 2017, Olagunju and Olanrewaju, 2020).

5.2.5 Sustainability criteria and certification scheme

To obtain a comprehensive understanding of the sustainability of marine fuels, it is necessary to consider environmental, social, and economic factors throughout their life cycle. Ashrafi, Lister et al. conducted an extensive review of academic literature and employed a multi-stakeholder participatory approach to identify and categorize 18 sustainability criteria, as illustrated in Table 5-2, for a systematic and consistent evaluation of marine fuels (Ashrafi et al., 2022).

Table 5-2. Economic, environmental, and social criteria for evaluating alternative marine fuels

Environmental	Economic	Social
• Life cycle GHG • Air pollutions • Ocean acidification • Ecosystem degradation • Depletion of natural resources • Land use change	• Capital expenditures • Operational expenditures • Fuel cost • Opportunity cost • Safety-related risk costs • Possible	• Regulatory compliance • Social acceptability • Ethics and social responsibility • Public health impact • Occupational health and safety

	regulatory penalty	- Socio-economic development

It is crucial that marine fuels used onboard ships are sustainable in terms of their impact on the environment, society, and the economy, and that their sustainability aspects are continuously enhanced. A life cycle perspective is essential to fully understand sustainability issues and facilitate informed policy decision-making, as well as to aid investment decisions (Andreea Miu, 2021)

From a regulatory perspective, there are several existing regulations that use sustainability criteria to evaluate the sustainability of fuels for transport, such as ICAO's CORSIA and the EU RED II. ICAO, a specialized agency of the UN like IMO, developed a framework to define not only which fuels are eligible but also to include sustainability criteria. CORSIA Eligible Fuels (CEF) consist of two types: Lower Carbon Aviation Fuels (LCAF) and Sustainable Aviation Fuels (SAF).

Table 5-3. Sustainability criteria and allocation choices in other transport policies (Wardenaar et al., 2012, Prussi et al., 2021)

Legislation	Region covered	Sustainability criteria	Allocation method
Renewable Transport Fuel Obligation (RTFO)	UK	• Certification: Third-party certification required for land-use consistency and LCA emissions verification. • GHG Reduction Threshold: Eligibility criteria established. • Sustainability Criteria: Includes land carbon stock, water quality and availability, soil health, air quality, biodiversity conservation, waste and chemical management, labor practices, land and water rights, and food security	System expansion (or substitution) approach whenever possible, if not allocation based on economic value
Renewable Energy Directive (RED II)	EU	• Certification: Third-party certification required for land-use consistency and LCA emissions verification. • GHG Reduction Threshold: Eligibility criteria established. • Sustainability Criteria: Measures to ensure soil quality, biodiversity, and deforestation prevention for biofuels.	Energy based allocation, except for electricity co-production for which it is a system expansion (or substitution)
Low Carbon Fuel Standard (LCFS)	California	• Required Certification: Voluntary third-party certification ensuring land-use consistency and verification of LCA emissions. • GHG Reduction Threshold: Eligibility criteria for GHG emission reductions. • Sustainability Criteria: Specific requirements for biofuels to preserve soil quality, biodiversity, and prevent deforestation.	System expansion (or substitution) approach whenever possible, if not allocation based on energy content
Renewable Fuel Standard (RFS)	US	• Certification Requirement: Validation of LCA assumptions. • Aggregate Compliance: Nationwide Land Use Change (LUC) monitoring	System expansion (or substitution) approach
CORSIA	International aviation sector	• Certification Needed: Required for validation. • GHG Reduction Eligibility: Established threshold for qualification. • Sustainability Criteria: Includes land carbon stock, water quality and availability, soil health, air quality, biodiversity conservation, waste and chemical management, labor practices, land and water rights, and food security	Energy based allocation

LCAF are fossil-based aviation fuels with lower life cycle emissions than conventional fuels, while SAF should be produced from renewable or waste-derived sources. To meet the CEF criteria, the life cycle GHG emissions of the fuel should be at least 10% lower than those of conventional fossil-based fuels, and the fuel should not be produced from biomass obtained from land with high carbon stock (ICAO, 2019b). The CEF should be supplied by fuel producers certified by an approved sustainable certification scheme. This scheme is an example of how IMO regulation and guidelines can incorporate certification schemes.

Figure 5-2 illustrates the processes and elements of sustainability certification between CORSIA and the International Carbon and Sustainability Certification (ISCC).

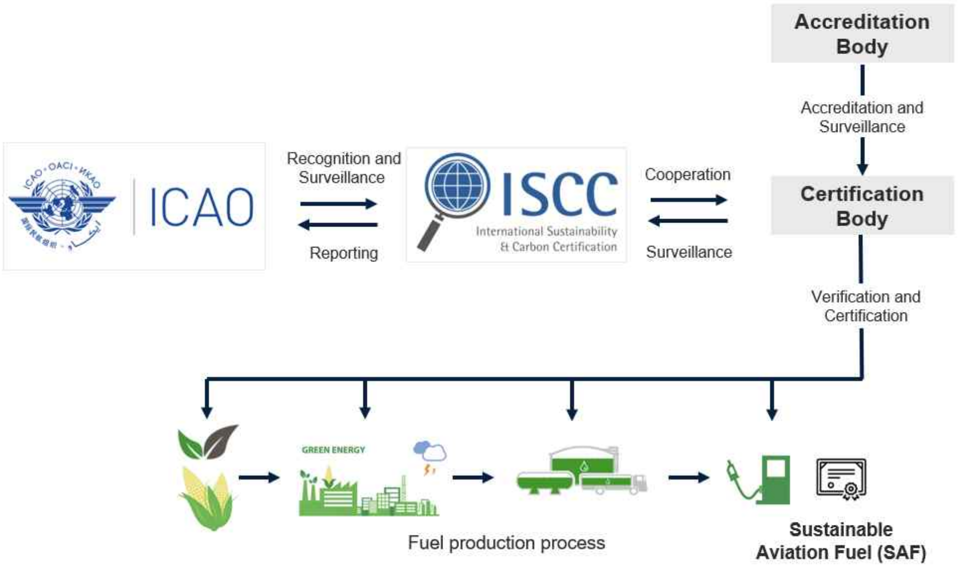


Figure 5-2. The processes and elements of CORSIA and ISCC

Regarding the certification schemes for GHG emissions, the IMO LCA guidelines are considering the inclusion of criteria and procedures for recognizing certification schemes that enable the use of certified actual emission values, which offer better performance than the default value. Reliable certification schemes are necessary to provide assurance if chemically identical fuels come from renewable sources or are produced from fossil fuels.

The sustainability criteria developed by ICAO to support CORSIA may be useful for IMO discussions. Considering the urgent need for the development of LCA guidelines for marine fuels, IMO may consider a phased approach: Phase 1 for life cycle emissions reductions and for feedstock not to be obtained from land with high carbon stock, and Phase 2 for additional criteria to address other aspects of sustainability, such as impacts to water, soil, and air.

In these sections from 5.2.6 to 5.2.8, the methodological aspects are analyzed among the investigated LCA studies. The most significant differences were found to be due to how the studies dealt with functional unit, sustainability criteria, co-product allocation, LUC, LCA database, and choice for attributional (A-LCA) or consequential (C-LCA) modelling.

5.2.6 Attributional (A-LCA) and consequential (C-LCA) modelling

The choice between attributional (A-LCA) and consequential (C-LCA) modelling (also known as marginal modelling) is crucial for the LCA methodology (Thomassen et al., 2008). The use of modelling is fundamental, and is selected at the phase of the goal and scope definition. The two LCA modelling terms are defined as below (Sonnemann and Vigon, 2011):

– Attributional approach: “System modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule.”

– Consequential approach: “System modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit.”

According to the European Council for Automotive R&D (EUCAR, 2017), the main differences between the two approaches are identified as shown in Table 5-4. The use of modelling is fundamental to the LCA methodology, and selecting the appropriate approach is critical.

Table 5-4. Main differences between attributional and consequential modelling principles

	Attributional approach	Consequential approach
Goal	Analysis of an average operation (e.g., on an annual basis)	Analysis of changes in operation (e.g., changes in demand)
Guiding question	For example, what are the potential environmental impacts of the average production of 1 ton of fuel (under different technical conditions)?	For example, what are the potential environmental impacts of a decrease in fossil fuel demand due to the increase in the use of alternative fuels in the transport sector?
Approach	Assigns elementary flows and potential environmental impacts to a specific product system typically as an account of the history of the product. Can use scenario analysis to project future technical situations	Studies of the environmental consequences of possible (future) changes within one or between multiple product systems

Although the distinct difference between the two approaches may result in different results of environmental impact, many LCA literatures (see Table A-1 List of LCA studies on the marine fuel) investigating marine fuel in their studies do not clearly indicate their choice between A-LCA and C-LCA. While some studies clearly indicate their choice. While some studies clearly indicate their choice with C-LCA (Bengtsson et al., 2011, Bengtsson et al., 2012, Brynolf et al., 2014), others selected A-LCA(Gilbert et al., 2018, El-Houjeiri et al., 2019, Malmgren et al., 2021, Thinkstep, 2019)

There have been some research studies that suggest C-LCA is more appropriate than A-LCA for supporting climate policy decisions, as it considers the consequences of product use or avoidance (Plevin et al., 2014, Brando et al., 2014). However, others argue that A-LCA is better suited for national emission accounting and environmental taxation (Prapaspongsa and Gheewala, 2017).

From a policy perspective, the A-LCA approach is used to account for physical flow (such as mass and energy) along the entire upstream process in the CORSIA framework, while the C-LCA approach is used to calculate indirect land use change (ILUC) GHG emissions through economic models that consider crop displacement (ICAO, 2019b). To estimate ILUC emissions for aviation biofuels, two economic models, GTAP-BIO and GLOBIOM, are used, which help reduce significant uncertainty in ILUC emission results (Prussi et al., 2021).

To set targets and define default values for WtW emissions for marine fuels in IMO, A-LCA should be prioritized due to its ability to reduce uncertainties, especially when allocation is required. Allocation is the process of assigning environmental impacts of a production process to different co-products. More details on allocation can be found in section 5.2.7. However, it may be necessary to apply some flexibility in using the consequential approach to capture the complexity of various feedstock-to-fuel pathways, such as biofuel emissions associated with ILUC.

A-LCA is employed in regulatory frameworks across various regions globally. Prioritizing A-LCA in the IMO's effort to establish targets and default values for WtW emissions for marine fuels can reduce uncertainties, particularly when allocation is required. However, to account for the complexity of several feedstock-to-fuel pathways, such as biofuel emissions associated with ILUC, some flexibility may be needed in applying the consequential approach.

5.2.7 Allocation method for coproduct

For a fuel production process that often produces multiple products, the environmental impacts corresponding to products should be defined and assigned. Two allocation methods are most widely applied to LCA studies. The first is a proportional allocation method, which divides inputs and impacts between products based on physical relationships such as mass and energy content or other characteristics such as market value. The second is called system expansion, which expands the system boundaries to account for the impact of displaced products. System expansion is the preferred LCA approach and it is often adopted in "consequential" LCAs. According to ISO recommendations, the allocation method should be based on physical parameters if system expansion is not allowed (ISO, 2006).

While ISO standards suggest the above principles, various regulations have their own methodologies for handling co-products. For instance, the European RED II and CORSIA use energy-based allocation methods while the US Renewable Fuel Standard uses system expansion. Other regulations, particularly biofuel policies, use different allocation approaches for each co-product (see Table 5-3) based on what the relevant legislation deems most appropriate. As shown in Table 5-3, different allocation methods have been adopted depending on regions. Various studies have shown that the amount of emissions generated to produce a product varies depending on the allocation method (Kyttä et al., 2022). Moreover, national governments can still end up with different regulations due to different interpretations. This circumstance not only lays the uncertainty for marine fuel producers and shipping industries, but also result in different regulations due to different interpretations for regulators.

For instance, the impact of biodiesel production is heavily influenced by the allocation methods used for by-products, resulting in substantial variability across the scenarios examined (Bengtsson et al., 2012). This is particularly evident when comparing LNG and HFO; the WtT emissions for LNG are 37–

93% higher than those for HFO, with the primary cause of this discrepancy being the different allocation principles applied to refinery emissions (Lindstad and Rialland, 2020).

While the system expansion allocation method presents complexities, physical allocation is relatively straightforward and yields stable outcomes over time due to its reliance on less ambiguous data. It is noteworthy that international regulations such as CORSIA and RED II favor energy-based allocation methods. For marine fuels and their co-products, particularly when the co-products are used in energy-related applications, allocation based on energy content could be the most appropriate. Although this approach does not eliminate all uncertainty, such as data issues, its straightforward nature is likely to enhance the robustness of related policies.

5.2.8 Indirect emissions

Indirect GHG emissions are those that occur outside the immediate product system or supply chain as a result of the activities of the reporting entity, such as the international shipping sector, and can be caused by factors like new sources of demand (Plambeck, 2012). One common example of these emissions is due to the relationship between biofuel demand and cropland expansion. The competition for cropland induced by biofuel production can result in direct land use changes, as well as crop acreage expansion on native vegetation and forested land (Austin et al., 2022). This expansion, in turn, increases carbon emissions and triggers indirect land use changes (ILUC) that contribute to GHG emissions, while also causing a rise in global crop prices (Khanna et al., 2011, Zheng and Qiu, 2020, Ahlgren and Di Lucia, 2014)

Table A-1 shows that although biofuels are used in many LCA studies on marine fuel, direct or indirect land use change (LUC) emissions have often been excluded in the system boundary of their analysis. They considered only direct emissions combusted in the marine engines.

It is noteworthy that LCA studies evaluating biofuels in other sectors (excluding shipping sector) typically assess direct(DLUC) or indirect land change use (ILUC) emissions associated with feedstock cultivation and biofuel production.

Several studies showed that GHG emissions due to DLUC can be positive or negative depending on the type of land use prior to the implementation of energy crops (Van Stappen et al., 2011, Guo and Gifford, 2002). For instance, if biofuel is produced on land with high carbon stocks such as forests, peatland or pasture, it can have a significant negative impact on the environment due to land-use change effects (DLUC) (Ben Aoun and Gabrielle, 2017).

Moreover, studies addressing the expansion of cropland to meet the growing demand for biofuel production include concerns regarding ILUC effects. Such effects could result in not only GHG emissions associated with indirect land-use changes but also numerous other undesirable effects(Woltjer et al., 2017).

From a regulatory perspective, policies should not ignore indirect emissions related to production of alternative fuels. While the CORSIA, LCFS, RTFO and RFS account for GHG emissions induced by ILUC, the RED II restricts the use of feedstock that present high risks of ILUC emissions (Mayeres et al., 2023). Nevertheless, estimated ILUC emissions are subject to uncertainties and vary significantly depending on the type of biofuel, feedstocks utilized, and production location(Prussi et al., 2021). Given that accounting for potential ILUC emissions could significantly alter the perceived effectiveness of certain alternatives in reducing GHG emissions, it is imperative that the IMO's LCA guidelines implement safeguards to mitigate these effects, even if they are not directly factored into the LCA emissions calculations.

5.3 Chapter summary and conclusions

The global shipping industry has indeed observed increasing commitments, popularity and interests of low- and zero-carbon fuels to achieve decarbonisation of the sector in time in spite of the scarcity of relevant studies with unified, harmonised LCA methodologies for informed decision-making on eligible alternative marine fuels. In this study, various preceding LCA studies and currently available regional policies as well as the aviation sector's approach have been closely examined with a view to facilitating the development of IMO LCA guidelines for marine fuels and looking to a better way to guide future LCA policy development and decision-making.

Key suggestions for developing proper IMO LCA guidelines can be summarised as below:

- The GHGs should include CO_2, CH_4, and N_2O since these represent the majority of GHGs emitted in shipping sectors
- GWP over 100 years should be considered in order for IMO policies to stay in line with the UNFCCC and other widely accepted international reporting standards for GHG emissions with a view to facilitating comparative assessment with other sectors
- For IMO policies, gCO_2eq/g_{fuel} and $gCO_2eq/MJ_{LHV,fuel}$ will be a more appropriate unit to introduce an effective way for calculation well to wake emissions based on fuel consumption
- For the purpose of setting the target and defining the default value for WtW emissions for marine fuels in IMO, A-LCA should be prioritised since it tends to reduce uncertainties
- The allocation method based on energy content could be the most suitable when the co-products are involved in energy based products
- A robust LCA methodology may need to account for the "consequential" GHG emissions associated with land use change (LUC) which can be addressed within one of the specific sustainability criteria.
- IMO may consider a phased approach on sustainability criteria: phase 1 for life cycle emissions reductions and for feedstock not to be obtained from land with a high carbon stock and phase 2 for additional criteria to address other aspects of sustainability (e.g., impacts to water, soil, and air

6 A FRAMEWORK FOR DETERMINING THE LIFE CYCLE GHG EMISSIONS OF FOSSIL MARINE FUELS IN COUNTRIES RELIANT ON IMPORTED ENERGY THROUGH MARITIME TRANSPORTATION

6.1 Introduction

This study was motivated by the limitations of current life cycle assessment frameworks, which lack proper guidelines for developing default life cycle values for energy sources that take into account supply chain activities and maritime transportation. To address this gap, this study aims to evaluate the 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. Specifically, this study seeks to answer the following two research questions: How can default GHG life cycle emission values for marine fuels be determined in energy import-dependent countries? And, to what extent do regional or geographic differences impact the GHG life cycle emission values of marine fuels, including emissions from maritime transportation?

The importance of these research 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.

6.2 Case study

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. Figure 6-1 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.

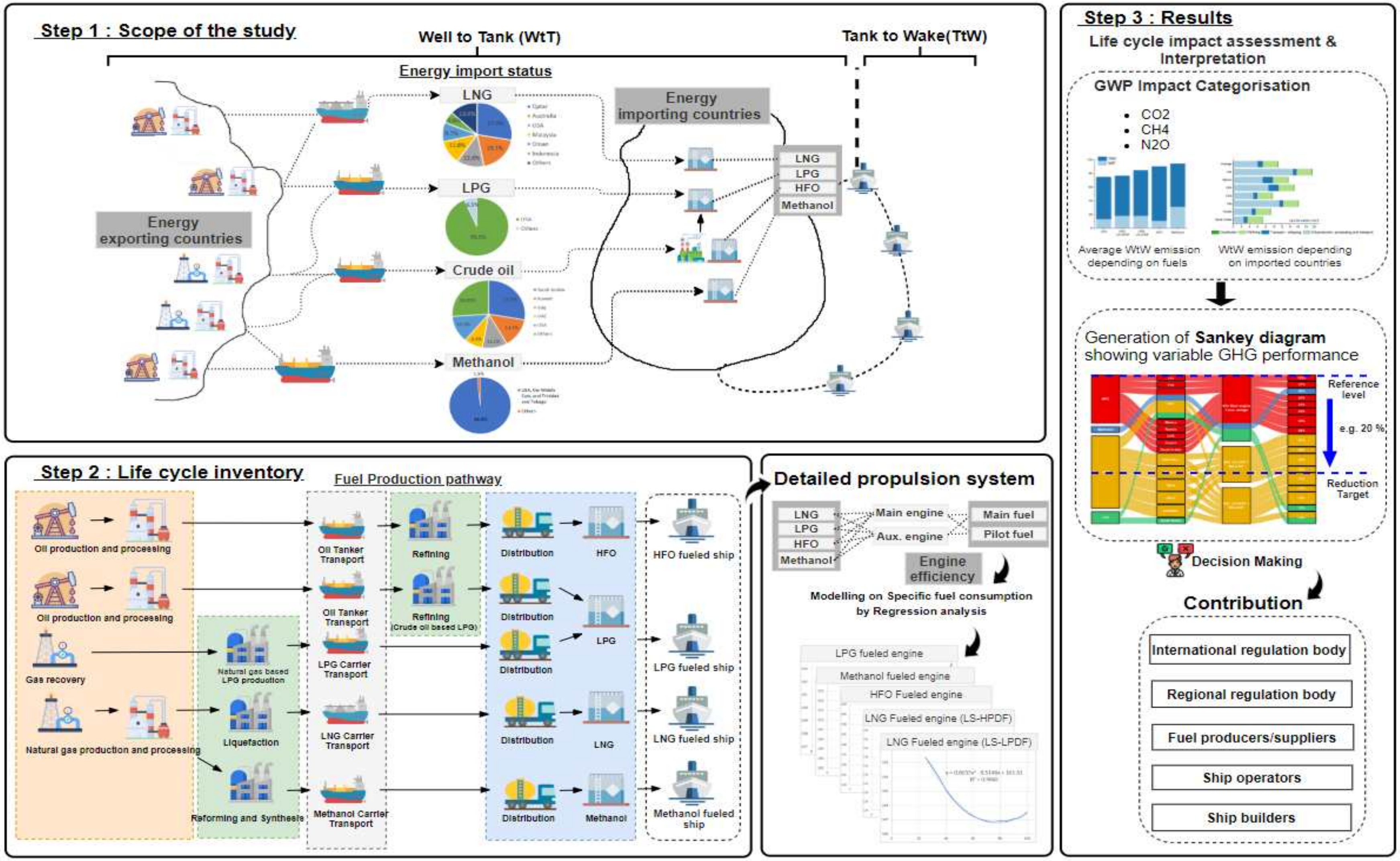


Figure 6-1. Life cycle assessment framework and methodology flowchart

6.2.1 Scope of the 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.

(a) 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 (Kouzelis et al., 2022, Fun-sang Cepeda et al., 2019, Ortega et al., 2021, Turnau et al., 2020). Amongst 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 6-1). In addition, IMO has developed safety regulations for LNG, LPG and methanol for their application to merchant vessels as shown in Table 6-2.

Table 6-1. Overview of key properties of different fuels (DNV, 2019a, Ampah et al., 2021)

	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	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
Energy density (MJ/L)	35.2	21.2	26.7	14.9

Table 6-2. 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

i. 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 Figure 1-1. 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). SOx and NOx 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 NOx emission from engines.

ii. 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℃ 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 SOx, NOx, and Particulate Matter (PM) (Bilgili, 2021b). 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).

iii. 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 ($C3H8$) and butane ($C4H10$) 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 SOx emissions and reduces GHG by approximately 17% compared to HFO (Brinks and Chryssakis, 2017). For a two-stroke diesel engine, NOx 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).

iv. Methanol

54 methanol-fueled ships are already in operation or on order according to DNV's online platform (DNV, 2022). Methanol ($CH3OH$) 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).

(b) 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 6-3. 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 6-3. 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

6.2.2 Comparison of GHG emissions between main fuel and pilot fuel

Table 6-4 indicates the result of specific fuel consumption (g/kWh) for main fuel and pilot fuel depending on engine load, using developed cubic or quadratic functions per each fuel engine (refer to Section 6.2.2). 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.

Table 6-4 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

Based on the data presented in Table 6-4, the calculation of their GHG emissions was performed. The results are illustrated in Figure 6-2, 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%.

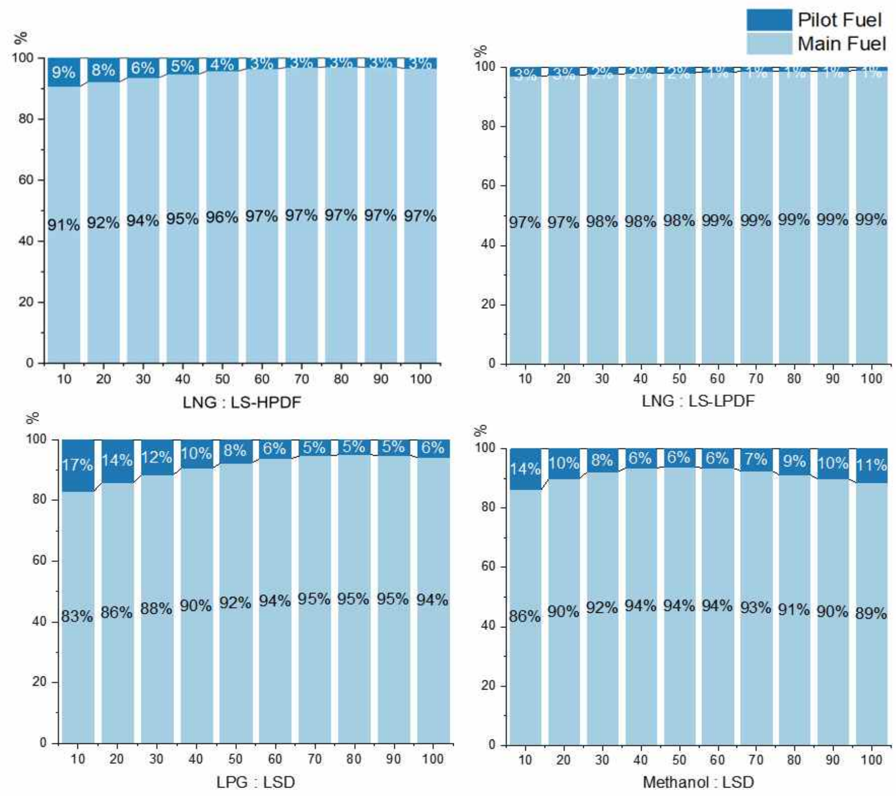


Figure 6-2. Ratio of GHG emissions emitted by main fuel and pilot fuel depending on engine load

6.2.3 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 life cycle into two stages: the upstream stage encompassing production to storage (Well-to-Tank), and the downstream stage (Tank-to-Wake), representing the use aspect.

(a) <u>Well-to-Tank Inventory Analysis</u>

Figure 6-3 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.

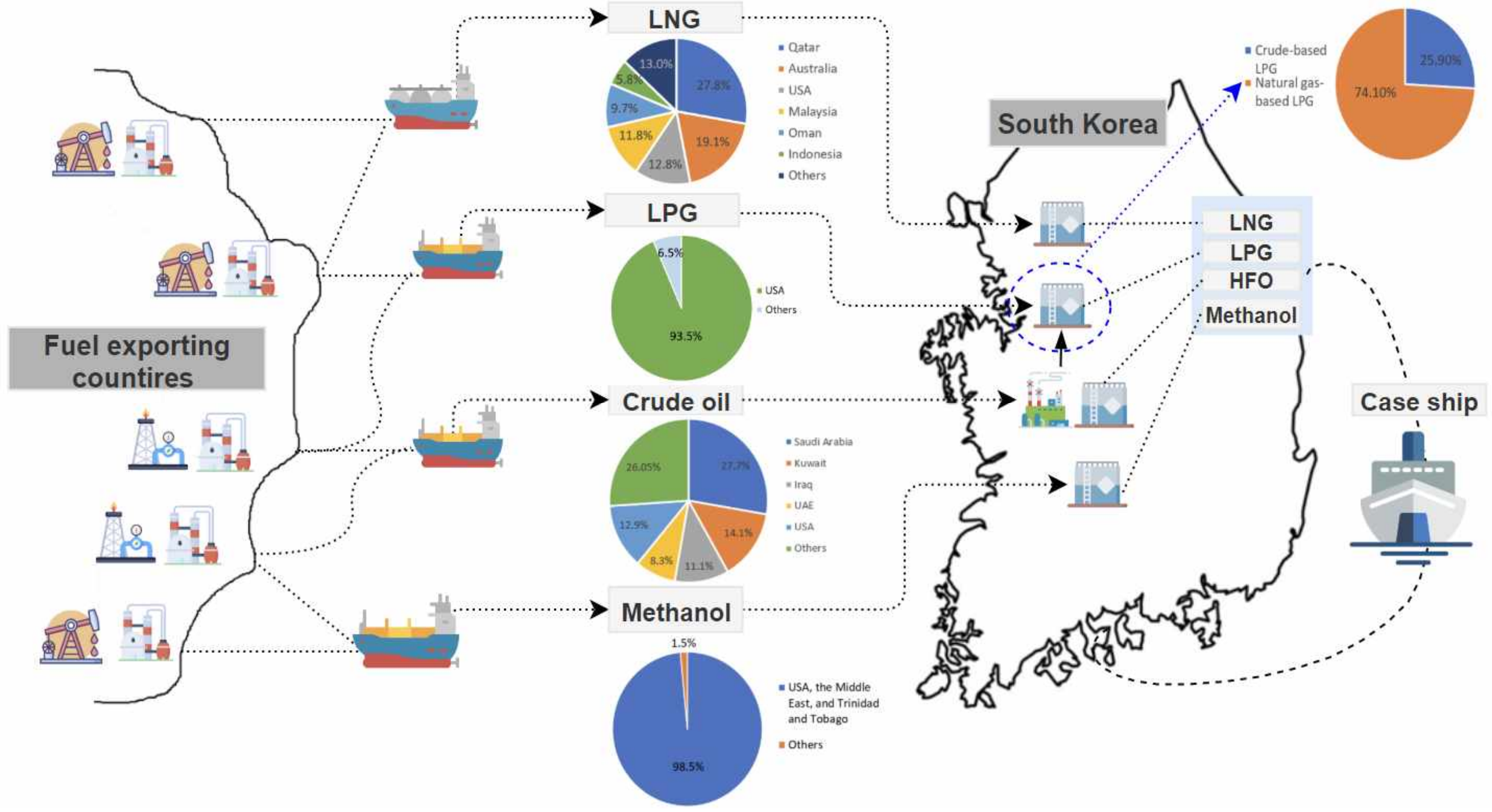


Figure 6-3. Imports of Crude oil, LNG, LPG and methanol to South Korea

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 Figure 6-4 in order to assess their WtW GHG emissions. In this study, the weighted average WtT GHG emissions associated with imported energy sources or fuels were estimated using the following equation.

- $\text{Average WtT GHG emission} = \frac{\sum_{i}^{n\ countries} (P_i \times \mathrm{WtT}_i)}{\sum_{i}^{n\ countries} P_i}$ (6-1)
- $WtT_i = Efs + Ec + Et + Ed$ (6-2)

where; P_i : the percentage(%) of a specific energy source or fuel imported to South Korea from a particular country, WtT_i : WtT emission value(gCO$_2$eq./MJ) of fuels imported from a particular country, based on production pathway in Figure 6-4, E_{fs} : emissions associated with feedstock extraction, recovery, and transport, excluding international maritime transportation, E_c : 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, E_t : emissions specifically linked to international maritime transportation for the feedstock or the finished fuel, E_d : emissions associated with the distribution phase, encompassing local delivery, retail storage, and bunkering

The pathways were also categorized into four steps: Efs, Ec, Et, and Ed, as shown in equation (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.

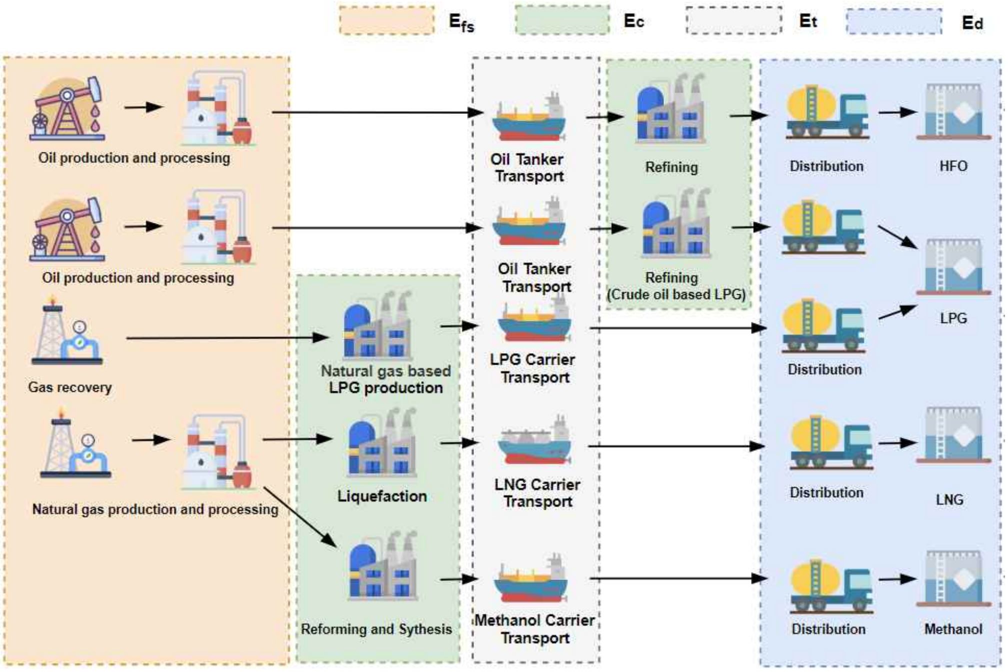


Figure 6-4 Production pathway modelling for HFO, LNG, LPG, and methanol in South Korea

i. 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 8,000 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 6-5 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(EFGHG) 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.

- $\mathrm{Et} = \frac{\sum_{i}^{n\ fuel} \sum_{j}^{m\ engine} M_{i,j} \times EF_{GHG}}{M_{cargo}\ x\ LHV}$ (6-3)
- $EF_{GHG} = Cf_{CO2} + Cf_{CH4}\ x\ GWP_{CH4} + Cf_{N2O}\ x\ GWP_{N2O}$ (6-4)

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 fueli, EFGHG: 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.

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 (Jang and Song, 2015, Choi et al., 2020).

Table 6-5 Ship specifications for maritime transportation

	Maritime transportation

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

ii. 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., 2017, Schuller et al., 2019). 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 6-5. 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., 2017, Schuller et al., 2019). It should be noted that unlike other fuels, methane loss in the distribution phase only occurs during LNG terminal and bunkering operations.

iii. 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.

iv. 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 55K methanol carrier traveling between the USA and South Korea.

(b) 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.

i. 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 6-6 summarizes general specifications and operational profiles of the selected ship.

Table 6-6 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: 7,250 kW × 88.7 RPM NCR: 5,597 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

The same specifications as MCR (7,250 kW × 88.7 RPM) and NCR (NCR: 5,597 kW × 81.4 RPM) were used in selecting the engine type using HFO, LPG, LNG, and methanol.

ii. 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 equation (4).

- $E = \sum_{i}^{n\ fuel} \sum_{j}^{m\ engine} M_{i,j} \times EF_{GHG}$ (6-5)

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

- $Et = \frac{E}{\sum_{i}^{n} M_i \times LHV_i}$ (6-6)

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 $fuel_i$

iii. Types of propulsion engines

- 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).

- 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, 2021).

- 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, 2020). 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, 2021b).

Based on selected propulsion engines above, the summary of emission data from propulsion engines can be found in Table 6-7. For all CO_2 emission factor between fuel consumption and CO_2 emission, it was taken by the 2018 EEDI Guidelines (IMO, 2018a). The emission factor for CH4 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 NOx 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.

Table 6-7. The data for estimating annual TtW GHG emissions for main engines using LNG, LPG, HFO and methanol

	LNG Fueled engine		LPG Fueled engine	HFO fueled engine	Methanol engine
Main engine type	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, Pavlenko et al., 2020, IMO, 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 x efficiency engine, Emissions per mass of fuel (g/kg fuel) = g/MJ fuel × LHV fuel (MJ/kg)					

iv. 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 6-8 presents specific fuel consumption and emission factors for the auxiliary engine. The emission factors obtained from the 4th IMO GHG study. Table 6-8 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).

Table 6-8 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

v. 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, the average main engine load at sea was determined as 72.5% of the MCR based on the ship's Abstract LOG data, reflecting the operational conditions of an actual vessel. These loads are then converted to fuel consumption using the specific fuel consumption (SFC) values for both the 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.

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

- $FC_{primary} = AML \times SFOC \times AD$ (6-7)
- $FC_{pilot} = AML \times SPOC \times AD$ (6-8)
- $FC_{aux} = AML \times SFOC \times AD$ (6-9)

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 6-8 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) =$0.0045x^2 - 0.559x + 146.51$ ($R^2 = 0.9566$) (6-10)
- SPOC (y) = $0.0019x^2 - 0.3024x + 15.367$ ($R^2 = 0.9414$) (6-11)

For LNG Fueled engine (LS-LPDF),

- SFOC (y) = $0.0033x^2 - 0.5148x + 161.61$ ($R^2 = 0.9965$) (6-12)
- SPOC (y) = $0.0004x^2 - 0.0807x + 5.5128$ ($R^2 = 0.9908$) (6-13)

For LPG Fueled engine,

- SFOC (y) = $0.0022x^2 - 0.2491x + 145.19$ ($R^2 = 0.8209$) (6-14)
- SPOC (y) = $0.0037x^2 - 0.5995x + 30.602$ ($R^2 = 0.9383$) (6-15)

For HFO fueled engine,

- SFOC (y) = $0.0065x^2 - 0.9238x + 198.72$ ($R^2 = 0.9674$) (6-16)

For Methanol fueled engine,

- SFOC (y) =$0.0002x^3-0.033x^2+1.8279x+273.18$($R^2 = 0.9933$) (6-17)
- SPOC (y) =$-0.0001x^3+0.0282x^2-2.0363x+63.508$($R^2 = 0.984$) (6-18)

6.2.4 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 life cycle 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.

- $$E_c = \frac{\sum_{i}^{n\ fuel} \sum_{j}^{m\ engine} M_{i,j} \times EF_{GHG}}{M_{cargo}} \quad (6\text{-}19)$$
- $$E_d = \frac{\sum_{i}^{n\ fuel} \sum_{j}^{m\ engine} M_{i,j} \times EF_{GHG}}{D} \quad (6\text{-}20)$$
- $$E_{tw} = \frac{\sum_{i}^{n\ fuel} \sum_{j}^{m\ engine} M_{i,j} \times EF_{GHG}}{M_{cargo}\ \text{x}\ D} \quad (6\text{-}21)$$

where; Ec : emissions per LNG ton carried (tCO_2 eq./ton), Ed: emissions per voyage distance(tCO_2 eq./mile), Etw: 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 equations (6-3) and (6-4).

6.3 Analysis results

6.3.1 Comparison of WtT GHG emissions from fuels

Figure 6-5 indicates the results of WtT GHG emission 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 2.5g CO_2 eq./MJ for USA while average value is 1.3g 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 300K VLCC.

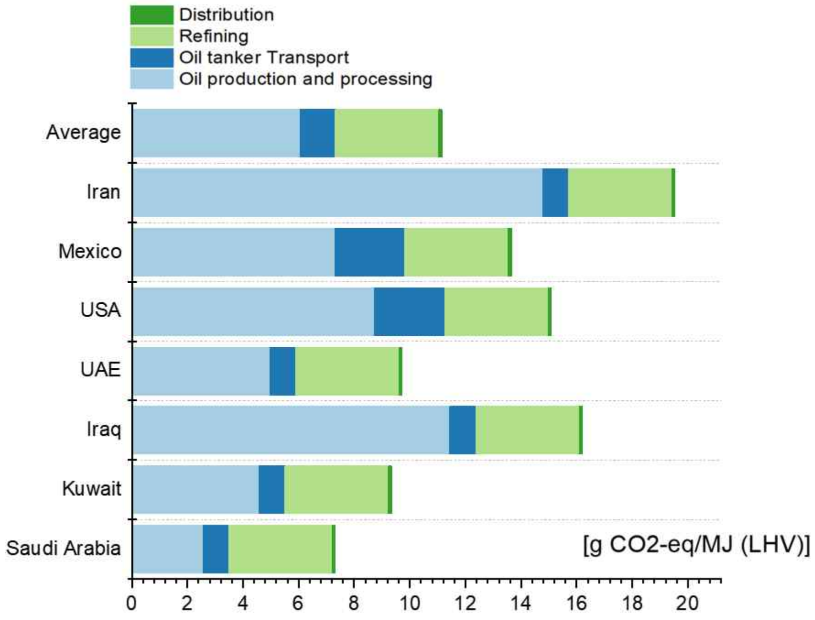


Figure 6-5. WtT GHG emissions for HFO depending on imported countries

Figure 6-6 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 6-9 (Choi and Song, 2014).

Table 6-9. 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

On the other hand, transportation emissions by LNG carriers have a wide range of emissions from 2.26 gCO_2 eq./MJ to 5.97 gCO_2 eq./MJ. Notably, Indonesia and Malaysia demonstrate comparatively lower emissions, with values of 2.26 g CO2 eq./MJ and 2.43 gCO_2 eq./MJ, respectively. In contrast, Australia's transportation emissions amount to 4.11 gCO2 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.

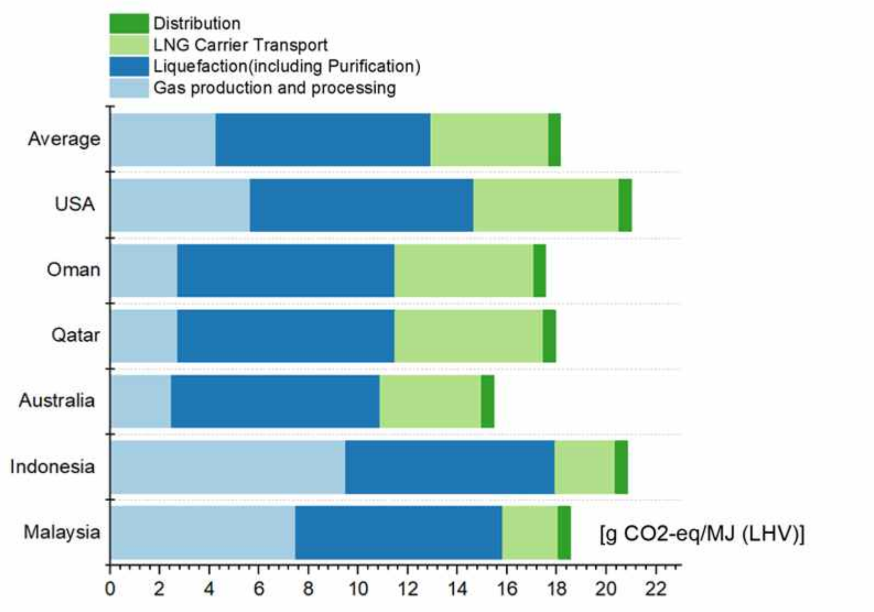


Figure 6-6. WtT GHG emissions for LNG depending on imported countries

As depicted in Figure 6-7, 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.

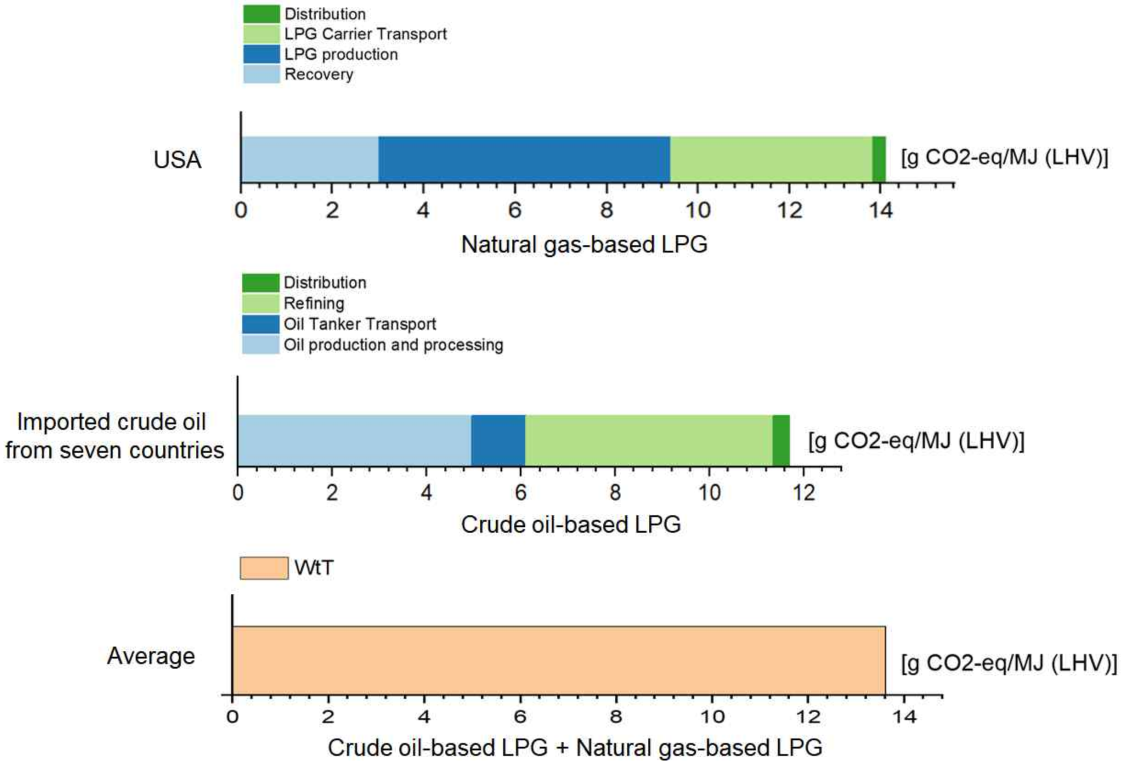


Figure 6-7. WtT GHG emissions for crude oil-based LPG and natural gas-based LPG

For methanol, the WtT emissions are determined to be approximately 20.72 g CO2 eq./MJ, as shown in Figure 6-8. These values are derived from the utilization of the GREET model developed at Argonne National Laboratory, combined with transportation emissions data for a 55K methanol carrier.

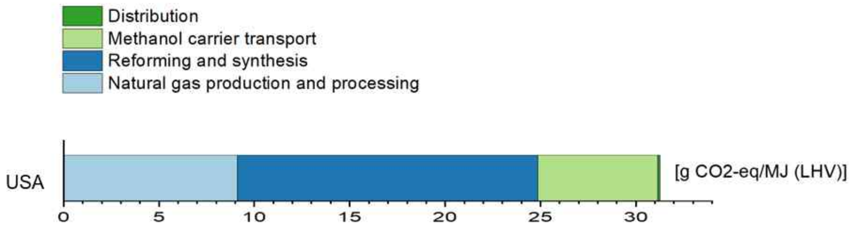


Figure 6-8. WtT GHG emissions for methanol

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 Figure 6-5 and Table B-6 in the supplementary material.

6.3.2 Comparison of TtW GHG emissions

Figure 6-9 compares estimates of the annual TtW emissions from ships using HFO, LNG, LPG and methanol fuels when using their main and auxiliary engines. Overall, compared to emissions from main engine, one from auxiliary engine have ranges of 5.2 to 7.3% of total TtW GHG emissions.

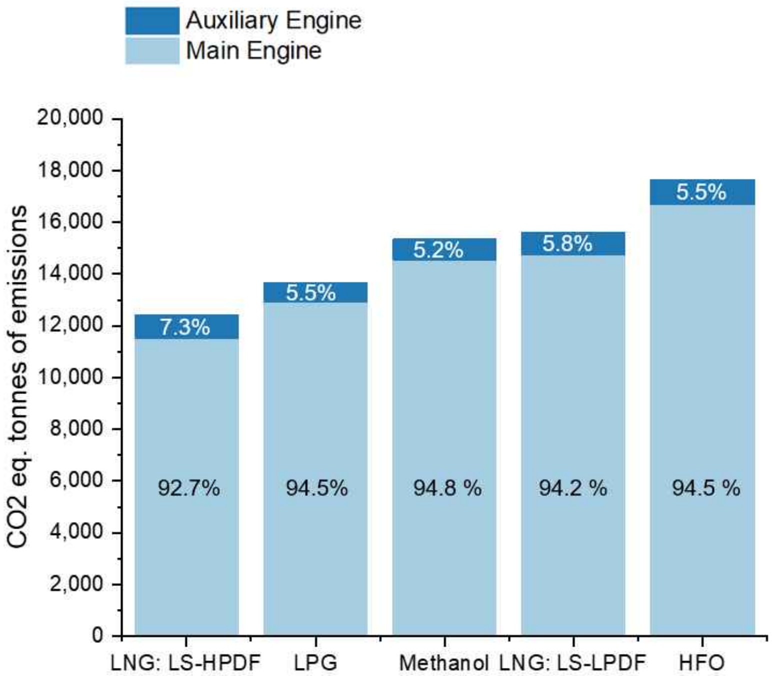


Figure 6-9. Annual TtW GHG emissions for HFO, LNG, LPG and methanol fuel (at average main engine load: 72.5% of MCR and operation days at sea: 250 days)

Figure 6-10 also illustrates average GHG intensity of the energy used on board ships for a given year when all emissions from ships are considered only from main and auxiliary engines. The trend of GHG intensity between fuels is analogous to that of annual GHG emissions indicated in Figure 6-9. 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, 2022d). 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.

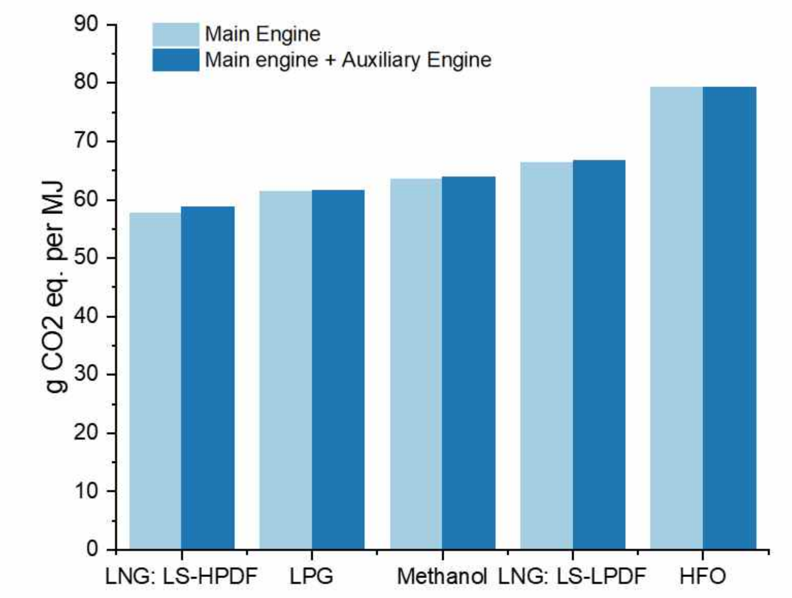
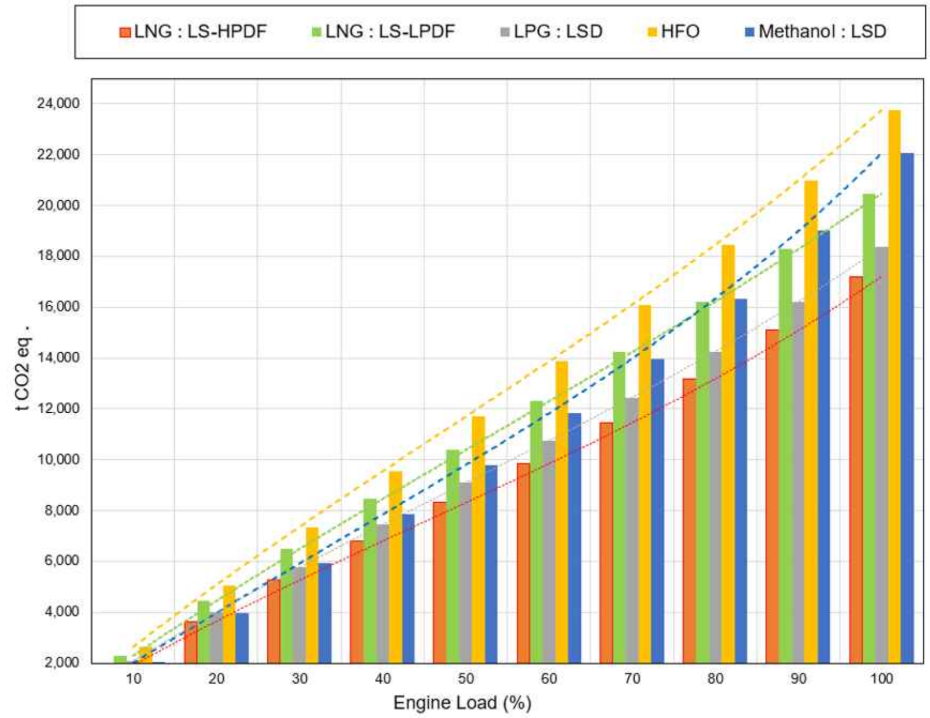


Figure 6-10 Average GHG intensity of the energy used on board ships

6.3.3 Comparison of GHG emissions from main engines



■ 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

Figure 6-11. GHG emissions from main engine using HFO, LNG, methanol and LPG fuel

Figure 6-11 presents the GHG emissions and their trends on main engines across four selected fuels, assuming they operate for the same period of 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 13981.95 and 14237.66 tons of greenhouse gases, respectively. At an engine load of 80%, the emissions for methanol and LS-LPDF are 16344.97 and 16225.77 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 B-26 in the supplement for more details.

6.3.4 Comparison of WtW GHG emissions

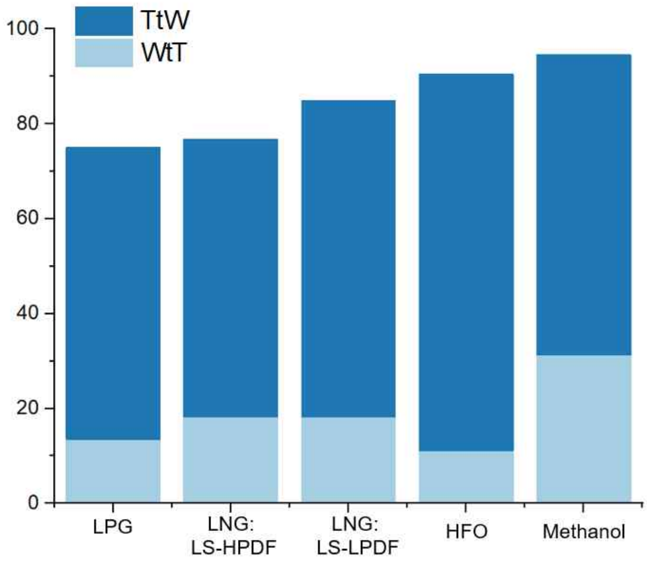


Figure 6-12 WtW GHG emissions for HFO, LNG, methanol and LPG fuel

Figure 6-12 shows the average WtW GHG emission that combines the results of Section 6.3.1 and 6.3.2. 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.

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.

6.3.5 Comparison on impact of maritime transportation

To investigate the impact of life cycle emissions associated with the regions of import, the three functional units of LNG fuel were examined as mentioned in Section 6.2.3.

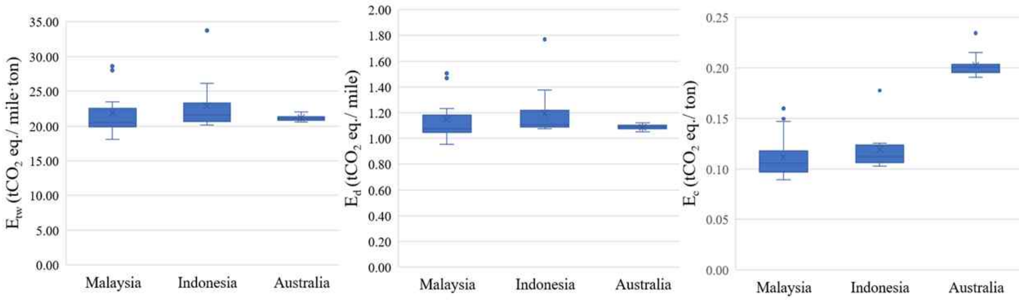


Figure 6-13. Comparison of GHG Emissions in LNG transportation to Korea via 125K LNGCs from Malaysia, Indonesia, and Australia

As indicated in Figure 6-5, the LNG import to Korea from Malaysia, Indonesia, and Australia is generally undertaken by 125K LNGCs with steam turbine. Figure 6-13 depicts the comparative analysis of average GHG emissions for these three units, namely E_c, E_d and E_{tw}. Ed 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 125K 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 Figure 6-14.

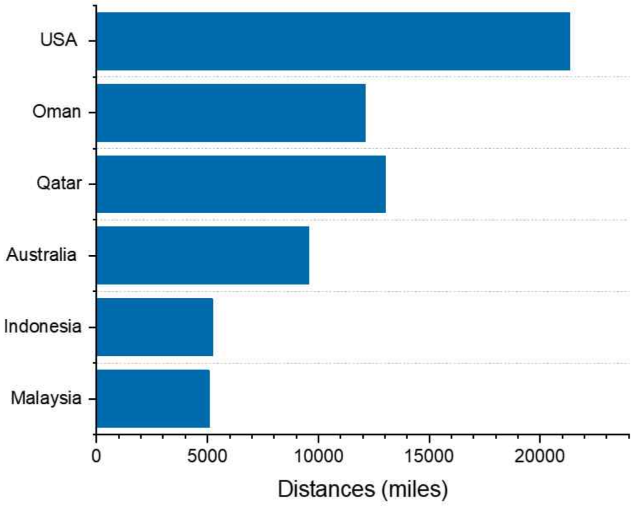


Figure 6-14. Variations in voyage distances based on regions of LNG import

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).

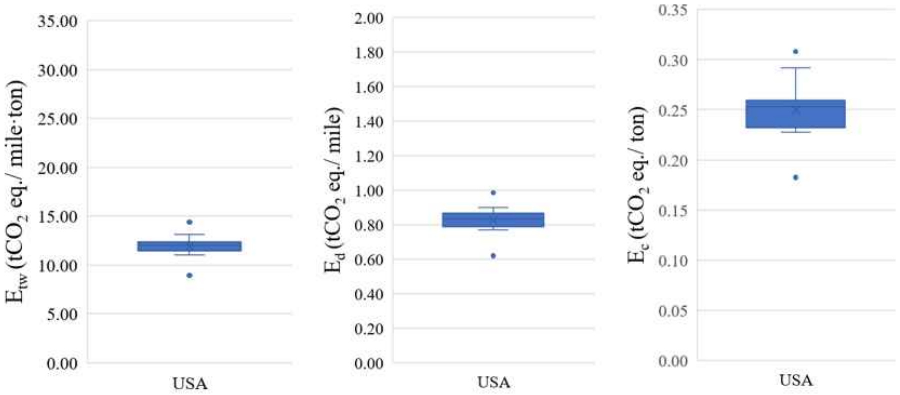


Figure 6-15. Comparison of GHG Emissions in LNG transportation to Korea via 174K LNGCs from USA

A straightforward comparison of E_{tw} between 125K LNG carriers equipped with a steam turbine and 174K LNG carriers utilizing LS-HPDP for LNG transportation to Korea, as illustrated in Figure 6-13 and Figure 6-15, 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 Limitations and Future Research Directions. Nevertheless, it is worth noting that the E_c 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 174K 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 voyage miles to South Korea, as shown in Figure 6-14. Hence, the distance from the energy source can have a relatively significant impact on GHG emissions per LNG ton or MJ carried.

6.4 Chapter summary and conclusions

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.

- 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).

- 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 emission for different countries. Research findings offers 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.

7 A PROSPECTIVE LCA FRAMEWORK FOR SUSTAINABLE RENEWABLE FUELS IN INTERNATIONAL SHIPPING: HYDROGEN-BASED E-FUELS

7.1 Introduction

In response to growing environmental concerns, the shift from conventional fossil-based marine fuels to sustainable alternatives has become a critical focus for policymakers. However, existing policy frameworks are inadequate for effectively assessing the impact of these alternative fuels on the ambitious GHG reduction targets set by the IMO. The need for a comprehensive assessment framework is particularly acute in the context of integrating renewable e-fuels into international shipping, a sector currently on the verge of a decarbonization transformation.

This study aims to fill the knowledge gap by establishing a holistic life cycle GHG impact assessment framework for the maritime industry's decarbonization pathways under various fuel adoption scenarios. By conducting an in-depth analysis of hydrogen-based e-fuel production pathways and the fleet emissions,

The two main research questions explored in this study are: How can a comprehensive framework be developed to assess the extent to which the integration of these fuels might contribute to the attainment of the GHG targets established for 2030, 2040, and 2050, as mandated by international shipping regulations? To what extent can sustainable marine fuels reduce GHG emissions, particularly when compared to conventional fossil-based marine fuels?

7.2 Case study

7.2.1. Scope of the study and framework

As shown in Figure 7-1, 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 life cycle assessment of marine fuels under the current infrastructure and existing ships. In addition to HFO, four marine fuels, namely, liquefied natural gas (LNG), methanol, ammonia and hydrogen have been selected as suitable sustainable fuel candidates for the purpose of comparing WTW GHG reduction potentials with fossil-based fuels.

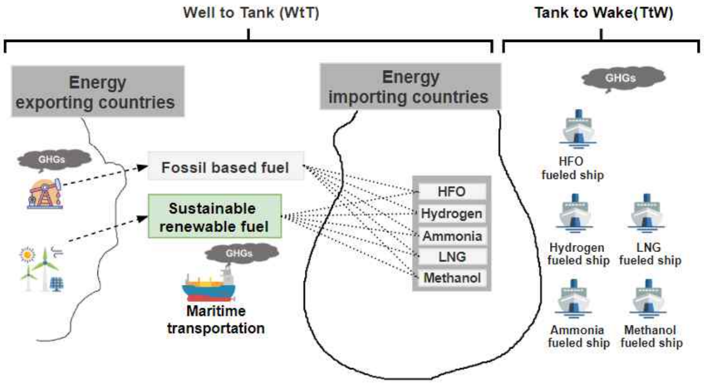


Figure 7-1. The scope of this study and selected fuels

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. Based on a one-hundred-year time horizon impact assessment (GWP100), their global warming potentials were selected 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. This study assumed that all the fuels in South Korea are imported via only maritime transportation. 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.

The year 2022 was chosen to represent the present state because it is the most recent year for which sufficient data are available to conduct a WTW analysis. The years 2030, 2040, and 2050 were selected to represent the future state because they are the target years for most of the energy policies utilized in the predictions. For this purpose, this study adopted prospective life cycle assessment (pLCA) to address emerging technologies and their expected environmental performance at a time in the future when the technology is likely to have matured.

The following prospective LCA framework was so proposed to compare the well-to-wake GHG emission impacts of a marine fuel bunkered in energy importing countries. 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. Figure 7-2 shows the methodology applied in this study.

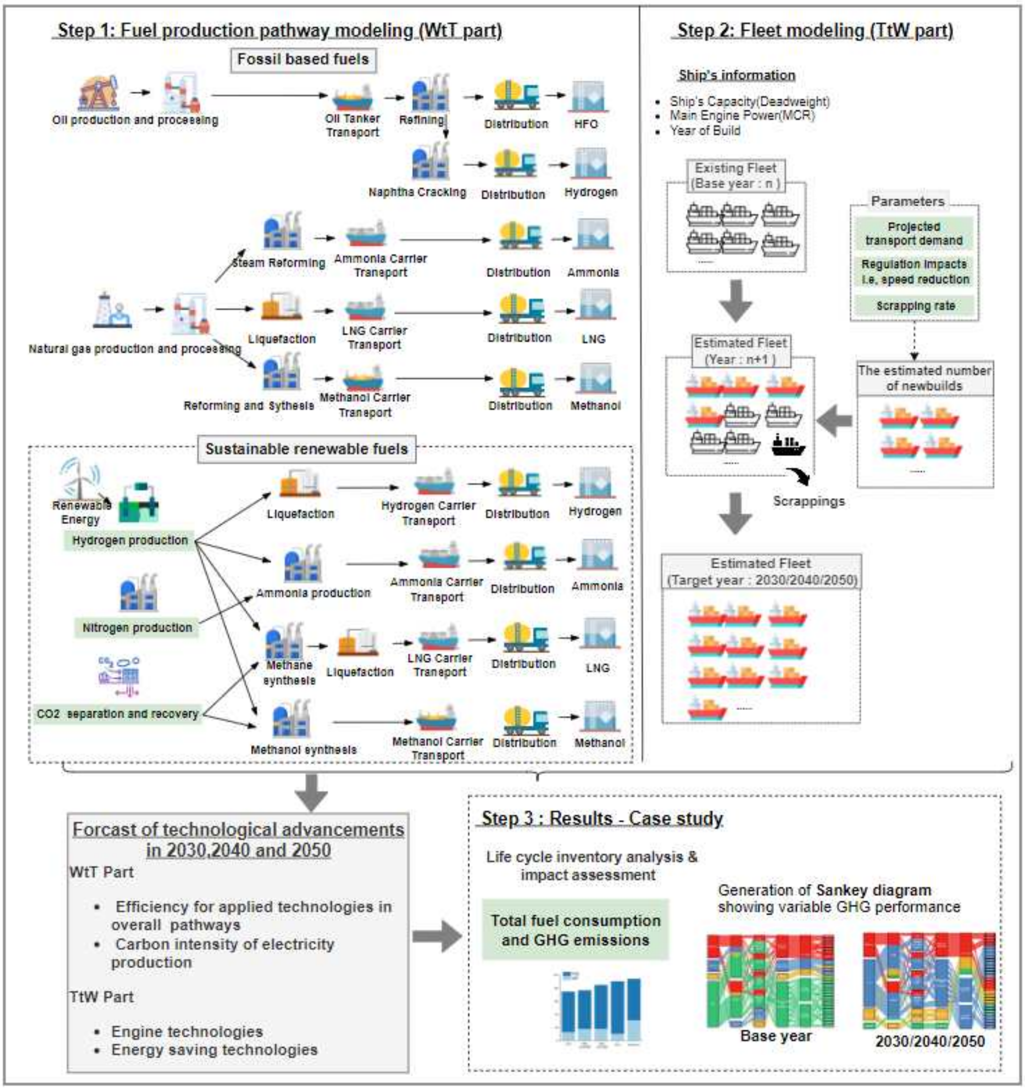


Figure 7-2. Life cycle assessment framework applied in this study

7.2.2. Step 1 Fuel production pathway and emission modelling: WtT Part

(a) Marine fuels selected

HFO was chosen as a baseline for assessing the life cycle GHG emissions linked to conventional fossil fuels. Additionally, four hydrogen-based e-fuels-hydrogen, ammonia, methanol, and LNG-were selected. This study delved into their production pathways, considering both fossil and renewable sources, to evaluate their potential for reducing life cycle GHG emissions.

Hydrogen is generated from a primary energy source and subsequently utilized to produce energy through internal combustion engines or fuel cells. Hydrogen serves as a clean energy source, generating only water as a by-product (Balat, 2008). Hydrogen has a very high calorific value compared to conventional fossil fuels. Hydrogen combines with other atoms to form the products such as water, ammonia, and methane. More notably, hydrogen can store intermittent renewable energy sources through the process of converting renewable energy to gaseous energy as an alternative to other storage systems such as batteries (Shi et al., 2020).

LNG, primarily methane (CH_4), liquefies at -160℃ under normal atmospheric conditions (Holzer et al., 2017). Compared to traditional fuels like HFO, natural gas significantly reduces emissions of SOx, NOx, and Particulate Matter (PM) (Bilgili, 2021b). Consequently, the 4th IMO GHG Study observed a 150% rise in methane emissions from ships from 2012 to 2018, attributed to the growing use of LNG as fuel. Nevertheless, LNG's environmental benefits are somewhat offset by the release of unburned methane during combustion in LNG-powered engines.

Methanol (CH3OH) is a straightforward alcohol currently employed as a power source for commercial vessels. Its liquidity at atmospheric conditions renders it more manageable than LNG (Oloruntobi et al., 2023, Verhelst et al., 2019). Methanol can be seamlessly integrated into existing shore infrastructure designed for conventional fuels with minimal and cost-effective adjustments (de Fournas and Wei, 2022). Nevertheless, it qualifies as a low-flashpoint and toxic fuel, necessitating careful onboard handling (Bilgili, 2021a). Methanol is already available worldwide for distribution and storage. As of 2023, 88 of the world's largest international ports have established methanol bunkering infrastructure, with 54 methanol-fueled ships either operational or on order (DNV, 2022).

Ammonia (NH3) is a synthetic product having one nitrogen atom and three hydrogen atoms. It has about half the energy density compared to conventional fossil fuels and it does not have to be stored in pressured or cryogenic tanks because of property of a liquid form at -33 °C. Although it is easy to store and handle on a ship, ammonia requires 4.1 times more volume than the conventional fuels such as HFO (Korean Register, 2019). The hydrogen produced by renewable energy sources is potential feedstocks to produce ammonia with net zero CO_2 emissions before being combusted by onboard engines (Giddey et al., 2017). However, ammonia has a nitrogen atom and it can promote the NOx formation in combustion process if its condition is suitable for formation. So, current IMO regulations require the addition of treatment system such as selective catalytic reduction(SCR) for ammonia engines to minimize NOx emissions (Zincir, 2020). According to Sixth Assessment Report from the IPCC (AR6), N_2O has the impact with 276 times on the Earth’s temperature than that of CO_2. Ammonia is a toxic substance and its high slip concentration during the combustion event results in health risks and eutrophication (Hansson et al., 2020). Although ammonia is difficult to burn since high ignition energy is required, internal two-stroke ammonia engines are currently being developed, which are expected to be commercially available by as early as 2024, followed by a retrofit package for the gradual rebuild of existing maritime vessels by 2025 (MAN Energy Solutions, 2021a).

(b) *Production pathway for fossil based fuels and sustainable hydrogen based e fuels*

The fuels examined in this study can be classified into two categories: fossil fuels and sustainable renewable fuels. Fossil fuels are derived from finite resources, such as crude oil, natural gas, and coal. Sustainable renewable fuels are derived from renewable sources such as water or air, using renewable electricity. Figure 7-3 shows the WtT pathway modelling for the selected marine fuels in this study. The more detailed data used in this study are summarized in the supplementary material.

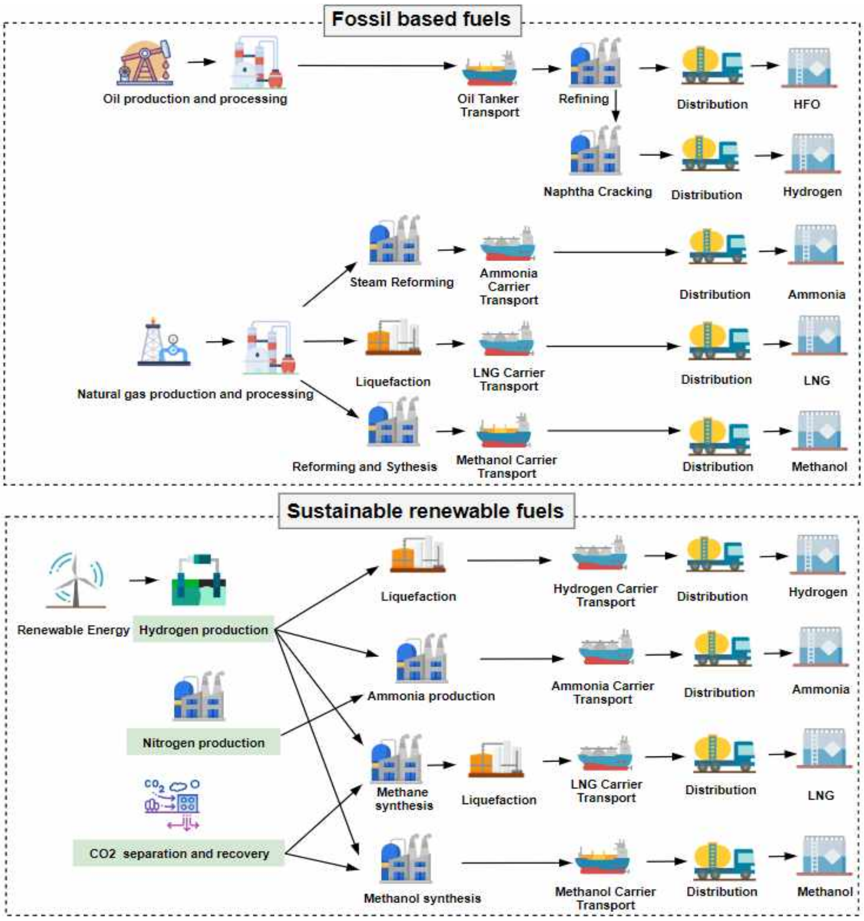


Figure 7-3. WtT pathway modelling for HFO, Hydrogen, Ammonia, LNG and methanol in this study

i. Heavy fuel oil (HFO)

South Korea imports crude oil from eight major producing countries via maritime transportation. These countries account for more than 80% of South Korea's total crude oil imports (Korea Petroleum Association, 2022). HFO is produced from this crude oil production through domestic refineries. The GHG emission data for HFO production was collected from the our previous study (Ha et al., 2023).

ii. Hydrogen

Hydrogen can be produced from two major : fossil fuels and renewable sources.(Shi et al., 2020, Bareiß et al., 2019). Approximately 75% of the annual global hydrogen production stems from hydrogen derived from natural gas (Birol, 2019), while South Korea's hydrogen production is dominated by by-product hydrogen, which is extracted during naphtha cracking, a petrochemical process. (Yoo et al., 2018). In this study, as fossil based fuels, hydrogens from both naphtha cracking processes and steam methane reforming (SMR) processes were mainly considered. Considering hydrogen production and sales in South Korea, the weighted average emission value was sought (Korea Energy Agency, 2018, Choi et al., 2020).

While approximately 4% of the total hydrogen output currently originates from water electrolysis that utilizes renewable energy sources (AlZahrani and Dincer, 2021), it is projected to increase to 22% by 2050 due to the growing global interest in renewable energy (Godula-Jopek, 2015, Arsad et al., 2023). In the realm of renewable hydrogen production, there are three dominant technologies used for water electrolysis: alkaline water electrolysis (AEL), proton exchange membrane electrolysis (PEM), and solid oxide electrolysis cells (SOEC) (Carmo et al., 2013, Kim et al., 2018, Donald et al., 2023). In this study, the PEM and AEL techniques were deliberately chosen as the favored avenues for pursuing renewable hydrogen production. The energy consumption for PEM and AEL, which refers to the energy required for the electrolysis of water into hydrogen, is estimated at 190 MJ / kg_{H2} and 172 / kg_{H2}, respectively. These estimates are based on energy efficiency values of 63% and 70% for PEM and AEL (Liu et al., 2020a). AEL can achieve higher efficiency in comparison to PEM electrolyzers due to its elevated electrolyte conductivity (Aydin and Dincer, 2022).

Before efficient maritime transportation of hydrogen, it needs to be liquefied at 253° C through liquefaction processes (Deniz and Zincir, 2016, Ratnakar et al., 2021). Based on the refrigeration cycles, the hydrogen liquefaction processes are divided into two parts, namely: the precooled-liquefaction process and the cascade-liquefaction process. Given the present technologies, the majority of hydrogen liquefaction processes fall within the range of 5–8 kWh/kgLH2 (Yin and Ju, 2020). For this study, a value of 6.5 kWh/kgLH2 was selected.

Shipping hydrogen internationally in compressed gaseous form is economically unfeasible. Instead, liquefied hydrogen (LH2) is the most economical and efficient way to export energy from resource-rich regions like Australia to energy-deficient areas like Japan and Korea. a (Ratnakar et al., 2021, Wang et al., 2023, Noh et al., 2023). In this context, the study assumed the transportation of LH2 using a 150K carrier with steam turbine propulsion system between Australia and South Korea, with an emission of 4.6 g CO_2 eq./MJ (JTTRI, 2022).

iii. Liquefied natural gas(LNG)

Currently most of the LNG consumed in South Korea is imported from several countries. Given this, this study assumes all LNG to be produced overseas and imported to South Korea (KOGAS, 2020). The conventional LNG WtT emission data was collected from a previous study (Ha et al., 2023). While fossil LNG remains a significant GHG emitter, the imperative to reduce emissions in the shipping sector demands the adoption of renewable LNG (Mukherjee et al., 2023). To achieve carbon-neutrality for synthetic natural gas, the utilization of captured CO_2 from diverse sources, including waste streams, gases from industrial point sources or biogenic processes, and direct air capture (DAC), becomes crucial in the methanation process to produce methane. This process is complemented by the usage of H2 generated through electrolysis powered by renewable energy source(Welch et al., 2021, Kim et al., 2023a).

Various technologies exist for CO_2 capture from point sources encompassing solvent-based absorption, membrane separation, and physical adsorption processes. Among these, the amine-based absorption process stands out as a commonly employed method for capturing CO_2 from exhaust gases (Zhang et al., 2019, Choe et al., 2023). As an energy-efficient alternative to conventional absorption techniques, the pressure swing adsorption (PSA) process is regarded for post-combustion carbon capture from industrial flue gases (Deng et al., 2023, Bhattacharyya and Miller, 2017).

This study employed amine-based absorption and pressure swing adsorption (PSA) methods to capture CO_2 from industrial point sources. In this paper, the following supply chain is assumed after the separation and recovery of CO_2 from industrial point sources in South Korea: liquefaction of CO_2, maritime transportation of liquefied CO_2 to a designated site (Australia) where renewable energy-derived hydrogen is made available, and vaporization of CO_2 for subsequent methanation process. More detailed data regarding the required energy for these selected methods are summarized in the supplementary material.

Another approach to CO_2 capture is DAC, which involves capturing CO_2 directly from the atmosphere. These technologies have been developed by leading industrial pioneers such as Carbon Engineering (Canada), Climeworks (Switzerland), and Global Thermostat (USA). Based on data from Climeworks' experience, this study estimates that the electricity and thermal energy demand is 0.7 kWh/kg_{CO2} and 4.7 MJ/kg_{CO2} captured, respectively. A heat pump system with a Coefficient of Performance (COP) of 2.51, operating on grid electricity, is assumed to deliver the thermal energy (Deutz and Bardow, 2021).

Based on literature by (Naohiro Murata, 2021), this study considered the methanation through the co-reaction of CO_2 (from industrial point sources and DAC) and hydrogen using Sabatier reaction ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$) as a method for thermochemical methanation, as well as the subsequent cryogenic liquefaction of methane. During the Sabatier reaction via heterogenous catalysis, a maximum achievable efficiency of 83% was assumed, assuming exothermic reaction without external energy input (Schiebahn et al., 2015, Reiter and Lindorfer, 2015). More detailed data regarding the required energy for these processes are summarized in the supplementary material.

iv. Ammonia

In this study, two ammonia production pathways were considered either steam reforming(SMR: $CH_4 + H_2O \rightarrow CO + 3H_2$) of natural gas or water electrolysis for the hydrogen supply to the Haber-Bosch process($N_2 + 3H_2 \rightarrow 2NH_3$, where combination of hydrogen and nitrogen (3:1) takes place in an exothermic process), common method for ammonia produced commercially corresponding to >70% of global ammonia production (Kurien and Mittal, 2022). It is noteworthy that for the conventional SMR pathway, N_2 in the syngas is not produced with an air separation unit but by depleting the O_2 in the air during natural gas combustion for process heat, and thus does not explicitly contribute to life cycle GHG emissions (Liu et al., 2020a).

The South Korea was the 3rd largest importer of ammonia in the world. It imports natural gas based ammonia primarily from main four countries; Indonesia (25.9%), Saudi Arabia (23%), USA(14%), Australia(14%) (Lim et al., 2023). Due to a lack of available data, the WtT GHG emissions for ammonia production in the USA specifically were adopted from the latest version of the GREET model (Wang et al., 2021). The transportation data for an ammonia carrier was assumed based on the average emissions of an 83K ammonia carrier traveling between the USA and South Korea, with an emission factor of 8.43g CO_2 eq./MJ (JTTRI, 2022).

In addition to the natural gas SMR pathway, alternative ammonia can be produced through a synthesis process that uses nitrogen from air and high-purity hydrogen from water electrolysis (Liu et al., 2020a, Sánchez and Martín, 2018). The process of ammonia production using electrolysis includes three steps: water electrolysis, nitrogen separation from air, and the Haber-Bosch process(Olabi et al., 2023, Castellani et al., 2018).

For nitrogen production, several processes such as membrane air separation, pressure swing adsorption (PSA), and cryogenic air separation units (ASUs) are available to extract N_2 from the air (Gomez et al., 2020, Castellani et al., 2018). While membrane air separation is suitable for low-purity intermediate-scale N_2 production, it is not considered in this study (Capstick et al., 2023). This study focuses on high-purity N_2 production and thus employs cryogenic distillation columns and PSA. The hydrogen and nitrogen produced are subsequently compressed to the required synthesis pressure and fed into the Haber Bosch synthesis reactor (Smith et al., 2020). In this study, the energy demand of Haber-

Bosch process including condensation to produce NH3 was estimated to 1.17 MJ / kg NH3 (Liu et al., 2020a)

v. Methanol

Given the mature methanol synthesis pathway, the methanol produced from natural gas accounts for 90% of global methanol demand (Adnan and Kibria, 2020). Its key process includes steam reforming of natural gas and methanol synthesis reactor ($CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$) (Matzen and Demirel, 2016, Kajaste et al., 2018). In this study, the GHG emissions for methanol production in the USA were adopted from the latest version of the GREET model. The feedstock for methanol production in the USA consists of 74.7% natural gas from shale production and 25.3% from conventional recovery practices (Wang et al., 2021, Ha et al., 2023).

For e-methanol production, the feedstock of H_2 and CO_2 is the same as for e-methane, as described previously. Subsequently, both H_2 and CO_2 are pressurized and heated before being directed to the MeOH synthesis reactor, where CO_2 reacts with H_2 to produce methanol and water (Sun and Aziz, 2021, de Fournas and Wei, 2022). Using ASPEN modelling from the literature (Adnan and Kibria, 2020), the energy requirements for methanol synthesis and purification were estimated as an electricity consumption of 0.33 kWh/kg MeOH (Meunier et al., 2020). Based on our previous study (Ha et al., 2023), a 55K methanol carrier was chosen for maritime transportation. The emission value was adjusted to account for the distance between Australia and South Korea. Table 7-1 summarizes the fuel production pathway/technologies depending on feedstocks applied in this study.

Table 7-1. Classification of fuel production pathways in this study

Fuel type	Feedstock type	Source of feedstocks	Technologies for feedstock production	Conversion Process type for fuel production	Fuel Pathway Code
HFO	Crude oil	Fossil	Standard crude oil production	Standard refinery process	HFO
Hydrogen	Natural gas (CH_4)	Fossil	Standard NG production	Steam methane reforming and liquefaction	Hydrogen_NG
	Crude oil	Fossil	Standard crude oil production	Naphtha cracking processes and liquefaction	Hydrogen_Naphtha
	Water	Renewable	-	Water electrolysis (PEM and Alkaline electrolysis) and liquefaction	Hydrogen_PEM Hydrogen_ALK
Ammonia	Natural gas (CH_4)	Fossil	Standard NG production	Steam methane reforming and Haber Bosch process	Ammonia_NG
	Air and water	N_2: Renewable	- Cryogenic distillation - Pressure swing adsorption(PSA)	Haber Bosch process	Ammonia_PEM_Cryo Ammonia_PEM_PSA Ammonia_ALK_Cryo Ammonia_ALK_PSA
		H_2: Renewable	- PEM electrolysis - Alkaline electrolysis		
LNG	Natural gas (CH_4)	Fossil	Standard NG extraction	Standard LNG production including liquefaction	LNG _Fossil
	Air, industrial point source and water	CO_2: Renewable - DAC	- Solid sorbent DAC (Amine-based)	Methanation and liquefaction	LNG_PEM_DAC
		CO_2: Fossil -Industrial point source	- Amine solution absorption - Solid sorbent (Pressure swing adsorption)		LNG_PEM_Amine LNG_PEM_PSA LNG_ALK_Amine LNG_ALK_ PSA
		H_2 : Renewable	- PEM electrolysis - Alkaline electrolysis		
Methanol	Natural gas (CH_4)	Fossil	Standard NG production	Steam methane reforming and methanol synthesis	Methanol _Fossil
	Air, industrial point source and water	CO_2: Renewable - DAC	- Solid sorbent DAC (Amine-based)	Methanol synthesis	Methanol _PEM_DAC
		CO_2: Fossil -Industrial point source	- Amine solution absorption - Solid sorbent (Pressure swing adsorption)		Methanol_PEM_Amine Methanol_PEM_PSA Methanol_ALK_Amine Methanol_ALK_ PSA
		H_2 : Renewable	- PEM electrolysis - Alkaline electrolysis		

For the selected fossil fuels, a more detailed description of the production routes and their present status for HFO, LNG, and Methanol is provided in our earlier work (Ha et al., 2023).

(c) *Forecast of applied technology readiness of overall pathways for selected fuels*

i. Fuel production pathway

Technology readiness levels(TRL) for hydrogen-based e-fuel production is of major concern since it needs to address the challenges faced by these techniques for commercial implementation (Kurien and Mittal, 2022). Among the hydrogen production methods, steam methane reforming (SMR) stands as a well-established commercial technique (TRL 9), historically employed for hydrogen generation (Pinsky et al., 2020). Within the two selected electrolysis methods for hydrogen production, alkaline electrolysis emerges as the most commercially established and reliable approach for water electrolysis (Götz et al., 2016). In comparison, PEM electrolysis is a relatively newer technology (Ursua et al., 2011), currently holding a TRL ranging from 6 to 8 (Pinsky et al., 2020).

For large-scale production to become viable, challenges related to enhancing stack power density and reducing system size and complexity must be tackled. Nonetheless, the production capacity has shown rapid growth during this decade, indicative of commercial development. Based on energy efficiency values of 63% and 70% for PEM and AEL (Liu et al., 2020a) and data from other relevant literature (Ballal et al., 2023), this study assumes a gradual improvement in future electrolysis technologies, as outlined in Table 7-2.

When contemplating the utilization of carbon production as feedstock for hydrogen-based e-fuels such as methanol and methane, it is noteworthy that DAC technologies, which range from TRL 4 to 7 depending on the specific technology employed, are experiencing rapid improvements. These progressions are manifest in the successful exhibition of full-scale prototypes, which are primed for deployment (Kang et al., 2021, IEA, 2021). Based on this, the present study assumes an augmenting efficiency in DAC, as outlined in Table 7-2.

Table 7-2. Estimated potential improvement for current and future technologies

	Current	2030	2040	2050
Efficiencies(%) for current and future electrolysis technologies (Ballal et al., 2023)				
Alkaline	63	66	70	74
PEM	70	72	75	79
Future improvement of DAC's efficiency (Ballal et al., 2023)				
Heat pump system (kWh/kg $_{CO_2}$)	1.3	1.1	0.8	0.6
Electricity (kWh/kg $_{CO_2}$)	0.7	0.63	0.57	0.5
Future GHG emissions in maritime transportation compared to current GHG emissions				
GHG emission reduction levels (%)	-	14.5	62	80
The carbon intensity (gCO_2 eq./kWh) of future electricity production compared to current GHG emissions				
Grid mix electricity	560	200	140	80
Wind power	0.62	0.41	0.21	0
Photovoltaic	6.15	4.1	2.05	0

For methanol synthesis, the viability of renewable methanol plants depends on plant configuration, local conditions, feedstock availability, and access to renewable electricity. Methanol synthesis and distillation are mature technologies (TRL 8-9), especially when CO_2 and green hydrogen are readily available, as the production technology closely resembles that of traditional fossil fuel-based plants. (Kang et al., 2021).

For e-methane production, there are four primary CO_2 methanation pathways: thermochemical (Sabatier reaction), biochemical, photoelectrochemical, and electrochemical. In this study, we focus on the thermochemical methanation via the Sabatier reactor, which is already employed at a large scale for methane production using syngas from coal gasification. The process for manufacturing e-methane has been demonstrated at a smaller scale (Welch et al., 2021).

e-ammonia is synthesized through the combination of green hydrogen with nitrogen using the Haber-Bosch process which is projected to maintain its dominance for ammonia synthesis in the forthcoming decades, particularly on a large scale (Valera-Medina and Banares-Alcantara, 2020). For various nitrogen production technologies, namely a pressure swing adsorption (PSA), and cryogenic air separation units (ASUs) are mature technologies (TRL 9) (Rouwenhorst et al., 2020). Ammonia synthesis with the high-pressure Haber Bosch process are already industrially applied (TRL 8-9) (Rouwenhorst et al., 2021, Cardoso et al., 2021).

In this study, due to the mature state of the selected technology, we conservatively assumed that the energy required for the conversion processes of ammonia, methanol, and methane remains constant between now and 2050.

ii. Maritime transportation

When addressing GHG emissions from maritime transportation during the WtT stage, there is potential for improvement over time, due to the implementation of stringent regulations aimed at reducing the GHG intensity of energy utilized on ships, known as the GHG Fuel Standard (GFS) (IMO, 2023b). This study considers the minimum regulatory targets set by the FuelEU Maritime Initiative, outlined in Table 7-2. These targets involve a gradual reduction in GHG intensity over the years compared to the maritime transportation emission value calculated. The reduction starts with a 2% decrease in 2025 and may potentially reach up to 80% by 2050 (European Commission, 2023).

(d) Electricity production scenarios: grid's mixed electricity, and off-grid from renewable energy sources

Given the sensitivity of environmental impacts in e-fuel production to the electricity source (Kanchiralla et al., 2022, Kanchiralla et al., 2023), three scenarios have been examined. In the first scenario, all fuel and hydrogen production processes rely exclusively on electricity from renewable sources, specifically solar or wind power. In the second scenario, we consider a hybrid system, which combines an off-grid hydrogen production system with the conversion process using electricity from the grid's mixed sources (Cheng and Hughes, 2023). The third scenario involves using electricity from the grid's mixed sources. For these scenarios, we adopted emission factors for the electricity grid in 2022 and 2030 based on forecasts from Australia's National Electricity Market (NEM) (Department of Climate Change, 2022, Donald et al., 2023). However, due to a lack of data, the electricity grid's emissions for 2050 were estimated based on the global average provided by the International Energy Agency (IEA) (Abergel et al., 2017, Deutz and Bardow, 2021).

This study considered electricity generated from wind power and photovoltaic (PV). The system boundary was limited to the operational stage, excluding production, construction, and material disposal. Although operational emissions are minimal over the life cycle (Liu et al., 2021), the GHG emissions(0.62 $gCO_2eq./kWh$) associated with the operational phase of wind power were estimated with an average range of 0.49 to 0.74 $gCO_2eq./kWh$ (Hatch, 2014, Mallia and Lewis, 2013). For PV, an emissions value of 6.15 $g\ CO_2eq./kWh$ was selected (Marashli et al., 2022). In the absence of available data, this study assumed a gradual and uniform reduction in these emissions until 2050, as depicted in Table 7-2.

(e) <u>*WtT GHG emissions allocation*</u>

When calculating GHG emissions from the production of hydrogen-based fuels based on feedstock production and conversion process in Table 7-1, the allocated emissions (EF_i : gCO_2 eq./ MJ Hydrogen based fuels) from feedstock production to the total emissions of the final produced fuel and emissions(EC_i : $g\ CO_2$ eq./ MJ Hydrogen based fuels) from their conversion were determined using the following equation:

- $$E_{F\,i} = \sum_i^n E_{Feedstock\ \ i} \times \frac{Mass_{Feedstock\ \ i}}{Mass_{Hydrogen\ based\ fuel\ \ j}} \qquad (7\text{-}1)$$

- $$E_{Feedstock\ \ i} = \frac{ER_{Feedstock\ \ i} \times CI_{Electricity} \times 1000}{LHV} \qquad (7\text{-}2)$$

- $$E_{C\,i} = \frac{\sum_j^m ER_{conversion\ \ j} \times CI_{Electricity} \times 1000}{LHV} \qquad (7\text{-}3)$$

Where, EF_i : GHG emissions ($g\ CO_2$ eq./ $MJ_{\text{feedstocks}}$) for production of feedstocks (H_2, CO_2, N_2) used in the production of hydrogen-based fuels, Mass

$_{\text{Feedstock i}}$: Required feedstock mass flow for the production of each hydrogen-based fuel, ER $_{\text{feedstock\_i}}$: the energy requirement per unit of feedstock production (kWh /kg) for H_2, CO_2, and N_2, EC_i : Energy requirement per unit of conversion (kWh/kg) to the final produced fuel, $CI_{electricity}$: the carbon intensity (kg CO_2 eq./kWh) of electricity production, whether sourced from the grid or renewable sources.

7.2.3. Step 2 Fleet modelling (TtW part)

(a) Selected ships

The entire fleets in specific ship categories were collected through the IHS vessel database, which offers thousands of ship specifications, including built year, propulsion power, design speed, and dead weight tonnage (DWT). Considering that large ships are responsible for about 85% of net GHG emissions in the international shipping sector (IRENA, 2021), this study chose 2062 bulk carriers above 50,000 gross tons. Figure 7-4 shows the general specifications of the ships selected, including ship age, power, and DWT.

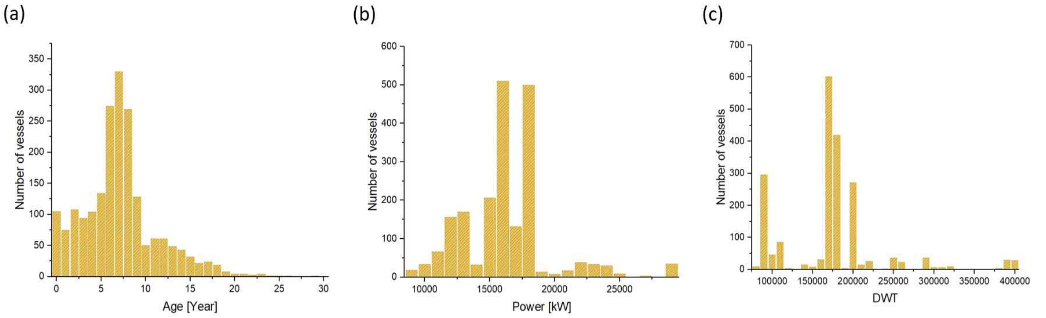


Figure 7-4. the selected ship's general specification: (a) ship numbers according to age (Year), (b) ship numbers according to power (kW) and (c) ship numbers according to deadweight (DWT).

(b) Fleet forecast modelling

To estimate GHG emissions from future fleets, the number of ships in the fleet was determined considering the main factors influencing the fleet size: transport demand, speed reductions due to regulations, and scrapping rates. First, the amount of transport work in the base year is defined, and future transport demand is predicted based on socio-economic model (GDP, population, and energy consumption). Next, the number of ships required to cover the required transport demand is determined after considering the details of the ships deployed. Additionally, the number of ships required to cope with the reduced transport work due to the decrease in the average speed of the fleet due to stricter regulations is also determined. Finally, the number of ships in a given year (2030, 2040, or 2050) is calculated as follows:

- $$SN_{year} = SN_{base\ year} + \sum SN_{transport\ \ demand} + \sum SN_{speed\ \ reduction} + \sum SN_{scrapping} \tag{7-4}$$

Where, $SN_{base\ year}$: the number of ships in the base year (2062 for bulk carriers), subtracting those that have been scrapped due to aging($SN_{scrapping}$), $SN_{transport\ demand}$: the number of ships added to the fleet due to increased transport demand, $SN_{speed\ reduction}$: the number of ships added to the fleet due to speed reduction in existing fleets, $SN_{scrapping}$: the number of newly built ships replaced those scrapped due to aging.

In considering the number of newly built ships directly replacing those scrapped due to aging, this study assumes a simplified scenario in which the total number of ships remains constant. In reality, factors such as changes in economic conditions or regulatory policies could influence the dynamics of newly built ships replacing those scrapped due to aging, and these factors are not explicitly considered in this model. However, it's important to note that this factor influences the GHG emissions of the entire fleet, due to the introduction of more efficient newly built ships or those using alternative fuels. Further details are elaborated in Section 7.2.4.

i. Projected transport demand

1) The total transport work for the base year

In this study, the calculation of transport demand utilized a supply-based metric known as transport work capacity. This metric is measured in deadweight tonne (DWT)-miles, which is a measure of the cargo-carrying capacity of a ship (IMO, 2021d). The estimation of transport work capacity in tonne-miles involved multiplying the trade volume in tons by the average nautical miles of operation. For this purpose, data from selected 2062 bulk carriers, along with their average operating speed and days at sea as indicated in Table 7-3, were used. Based on these parameters, the total transport work for the base year ($TW_{\text{base year}}$: 2022) was computed as follows:

- $TW_{\text{base year}} = \sum(DWT_i \times D_i)$ (7-5)

- $D_i = V_i \times AD_i$ (7-6)

where; DWT_i : Deadweight of a ship: , D : Vi : Average operating speed at sea, AD: Average days at sea per year

Table 7-3. The operation speed and days at sea depending on ship sizes

Ship size (Deadweight, ton)	Number of ships	Average operating speed at sea (Vi)	Average days at sea (AD)
60,000-99,999	306	11.8	214
100,000 – 199,999	1218	11.6	252
200,000 - +	538	12	258

2) The future transport work demand

The estimation of transport demands up to 2050 was based on the assumption that international seaborne trade correlates with socio-economic indicators (GDP, population, and energy consumption). This study chose the two scenarios: Low growth of OECD RCP 2.6 with gravity model and High growth of RCP 2.6 SSP2 with Logistics Model from the Fourth IMO GHG study (IMO, 2020), ones of the IPCC's climate models, for estimating future emissions. The SSP scenario indicates socio-economic indicators, such as GDP and population, while the RCP scenario represents GHG concentration levels through the radiative forcing value (unit: W/m2). To achieve a more conservative output, the Logistics Model with higher growth assumptions was adopted. Recognizing that the assumption of uniform growth across all segments of the shipping industry could introduce biases for or against specific sectors of the maritime domain, this study accounted for variations in growth rates among different segments and ship types. Specifically, the increased demand for the selected ship type, i.e., bulk carriers, was taken into consideration as shown in Table 7-4.

Table 7-4. Estimate of increased transport work for bulk carriers up to 2050

Scenarios	Unit	2022	2030	2040	2050
Low growth	bill ton-miles	28457	32918	38493	44069
	%	109	126	147	168
High growth	bill ton-miles	28457	37829	49543	61258
	%	120	159	208	258

To estimate the number of new building ships, this study assumed two ship categories to meet the increased transport demand ($SN_{transport\ demand}$), as shown in Table 7-5. The ship specifications were determined based on the average values of two capacity groups from 2007 bulk carriers: ships above and below 20,000 DWT. This specification was also applied when calculating the fuel consumption and its GHG emissions from the new ships added because of speed reduction and scrapping.

Table 7-5. Ship specifications of newly constructed ships

Ship size (Deadweight, ton)	Average Deadweight ($DWT_{average}$)	Avg. main engine power(kWh)	Average transport work of a ship per year ($TW_{average}$:)	Average days at sea (AD)
– 200,000	154,993	10,398	10,693,934,350	244
200,000 - +	252,386	13,938	18,753,275,809	258

The calculation of the number of new ships to be built in response to increased transport demand was determined using the following equation

- $$SN_{transport\ demand} = \frac{TW_{year} - TW_{base\ year}}{TW_{average}} \quad (7\text{-}7)$$

Where; TW_{Year} : Total estimated transport work for bulk carriers up to a specific year (2030, 2040, and 2050) based on the increase rate shown in Table 7-4, $TW_{average}$: The average transport work of a ship per year shown in Table 7-5.

ii. Impacts on speed reduction due to regulatory requirement for GHG reduction

Speed reduction represents one of the viable strategies to mitigate GHG emissions from ships or to align with stringent GHG regulations in the maritime sector, while minimizing substantial ship modifications (Han et al., 2023, Zhuge et al., 2021). When ships reduce their speed in adherence to GHG regulations to achieve a 40% reduction in carbon intensity for all ships by 2030 in comparison to the 2008 baseline, it results in a reduction in the transport capacity of the fleet. In order to compensate for the reduced transport capacity attributed to speed reduction, this study's model incorporates the addition of more vessels.

As a stimulus to reduce carbon intensity of all ships, ships are required to meet the requirement of two environmental indicators: the Attained Energy Efficiency Existing Ship Index (EEXI) as a technical requirement, and the Annual Operational Carbon Intensity Indicator (CII) along with its associated CII rating as an operational requirement but both apply to ships in operation. (Bayraktar and Yuksel, 2023).

Regarding EEXI regulation, approximately 65% of the tanker and bulk carrier fleet capacity already complies with EEXI standards, while some vessels will need to implement engine power limitations, potentially affecting the ship's speed (UNCTAD, 2022). Utilizing data from EEXI impact assessments carried out based on IHS and AIS (Løvstad, 2023), this study assumed a reduction in the average operating speed at sea, as presented in Table 7-6.

Table 7-6. Speed reduction due to EEXI impact since 2023

Ship size (Deadweight, ton)	Average operating speed at sea (Vi)	Speed reduction due to EEXI impact($V_{i\ EEXI}$)	Reduced speed due to EEXI impact
60,000-99,999	11.8	11.6	0.2

100,000 – 199,999	11.6	11.3	0.3
200,000 - +	12	11.8	0.2

For CII regulation, the annual operational CII for individual ships is calculated as the ratio of the total mass of CO_2 emissions (M) to the total transport work undertaken in a given calendar year. The ship is assigned a CII rating (A, B, C, D, or E), with 'A' indicating 'major superiority.' The rating thresholds will become increasingly stringent toward 2030. Regarding the impact of CII regulation by 2030, based on the impact assessment from the literature (IMO, 2021a), this study assumes that for vessels built before 2010, a 50% reduction relative to their design speed is applied, while newer ships are only required to achieve up to a 20% reduction due to their higher energy efficiency. The calculation of reduced ship speed (V_r) and the number of ships added due to speed reduction can be expressed as follows:

- $$V_r = \min\left(V_{i\,\mathrm{EEXI}}, V_{i\,\mathrm{CI}}\right) \qquad (7\text{-}8)$$
- $$V_{i\,\mathrm{CI}} = \begin{cases} 0.5 \times V_{i\,ref}\,, & \text{built year} < 2010 \\ 0.8 \times V_{i\,ref}\,, & \text{built year} \geq 2010 \end{cases} \qquad (7\text{-}9)$$
- $$SN_{\text{speed reduction}} = \frac{TW_{\text{base year}} - TW_{\text{reduced speed}}}{TW_{\text{average}}} \qquad (7\text{-}10)$$

Where; $V_{i\,\mathrm{EEXI}}$: the speed reduction due to the Energy Efficiency Existing Ship Index (EEXI) impact as shown in Table 7-6, $V_{i\,\mathrm{CII}}$: the assumed operating speed of the ship, adjusted to account for the impact of CII regulations, $V_{i\,\mathrm{ref}}$: the reference speed of the IHS vessel dataset, and $TW_{\text{reduced speed}}$: total transport work at reduced speed (V_r) in a specific year

iii. Impacts on scraping rate

As mentioned in Section 7.2.3.2, while the scrapping rate does not affect the total fleet size, this study assesses the GHG emissions of the entire fleet by simulating the replacement of aging ships with new ones operating on alternative fuels. Historical records indicate that over the past two decades, scrapping rates have rarely exceeded 3%, with intermittent peaks reaching approximately 4-5% for limited durations, and a slightly higher rate observed for bulk carriers compared to tankers and containers (Clarksons, 2020). Building upon the insights garnered from historical data, this study assumes an annual scrapping rate of 3% for the oldest ships within a specific segment, as determined by their transport capacity.

- $$SN_{scrapping} = \frac{Annual\ Scrapping\ \ rate\ (ton)}{DWT_{average}} \qquad (7\text{-}11)$$

Where, $SN_{scrapping}$: the number of ships scrapped due to age, $DWT_{average}$: The average deadweight of 2062 bulk carriers, categorized by deadweight (see Table 7-5)

(c) Annual fuel consumption estimation model

Fuel consumption from the main engine depend on the selected rated power, load factor, fuel type, engine type and year the engine was built. (Smith et al., 2015, Yuan et al., 2022). For calculating fuel consumption of 2007 bulk carriers assuming that heavy fuel oil (HFO) is used as the baseline fuel in the base year (2022), we adopted the following empirical equation to estimate the main engine specific fuel consumption (g/kWh, namely SFCME) for existing fleet (IMO, 2020, Jalkanen et al., 2012). This equation predicts the specific fuel consumption for a given engine load and age and identifies the main engine's most efficient load, which is typically around 80% of MCR. In this study, the average main engine load($Load_i$) for individua ship for individual ships was calculated as the ratio of the required propulsion power(P_i) at the average operating speed at sea to the reference power(P_1) as given in the IHS dataset.

- $$SFC_{ME,i} = SFC_{base} \times (0.455 \times Load_i^2 - 0.710 \times Load_i + 1.280) \qquad (7\text{-}12)$$

Where; SFC_{base} : the baseline of engine specific fuel consumption based on engine age and type(g/kWh) as shown in Table 7-7, $Load_i$: the average main engine load expressed as a proportion (P_i/P_1) ranging from zero to one.

Table 7-7. The SFC_{base} and SFC_{aux} given in g/kwh for different engine and year of built

	Before 1983	1984-2000	2001-
Main engine (SFC_{base})	205	185	175
Auxiliary engine (SFC_{aux})	225	205	195

In order to estimate a ship's propulsive power demanded when it is operating at a particular speed, the following equation was applied.

- $P_i = \frac{P_1 \times (\frac{Vi}{V_{ref}})^n}{\eta_w \times \eta_f}$ (7-13)

where; P_1 : the reference power as given in the IHS dataset (kW), V_{ref} : the reference speed of the IHS vessel dataset ,V_i : the average operating speed at sea (Knot), η_w : the weather modifier to the ship's propulsive efficiency, η_f : the fouling modifier, n : the speed ratio exponent to represent the relationship between speed and power(n=3)

In this study, the selected engines operate on ammonia, LNG, methanol, and hydrogen as their primary fuels, with the addition of pilot fuel. The annual fuel consumption of both the main engine and auxiliary engine for all fuels is calculated using the following equation.

- $FC_{Main} = SFC_{ME,i} \times P_i \times AD$ (7-14)
- $FC_{Aux} = SFC_{Aux,i} \times P_{Aux} \times AD$ (7-15)
- $FC_{Pilot\ ME} = SPOC_{ME,i} \times P_i \times AD$ (7-16)
- $FC_{Pilot\ Aux} = SPOC_{Aux,i} \times P_{Aux} \times AD$ (7-17)

where; SFC_{ME} : Main engine specific fuel consumption (g/kWh), FC_{Aux} : Auxiliary engine specific fuel consumption (g/kWh), P_{Aux} : Kilowatts (kW) at average auxiliary engine load, AD: Average days at sea per year $SPOC_{ME,i\ or\ Aux\ i}$: Specific fuel consumption (g/kWh) of pilot fuel for main engine or auxiliary engine.

Considering ship size for selected case ships, the power output of the auxiliary engine(P_{Aux}) is assumed to be 410 kW during sea operation while its specific consumption was selected depending on year of built (IMO, 2020).

(d) Projected readiness of technologies and their GHG emission factors

In projecting future fuel consumption and the consequent GHG emissions from newly integrated vessels due to measures such as speed reduction and scrapping, both the advancement and readiness of engine technologies and the degree of implementation of energy-saving technologies within these vessels become crucial considerations.

i. Engine technologies

The development of dual fuel engines utilizing diverse alternative marine fuels is progressing at an accelerated rate. Ammonia fuel engines currently stand at a TRL 5, denoting technology validation in a relevant environment. However, owing to swift advancements and escalating interest, both two-stroke and four-stroke engines are anticipated to achieve a commercial readiness level (TRL 9) concurrently in the late 2020s (Cardoso et al., 2021, Cames et al., 2021, Wärtsilä, 2021).

However, due to poor combustion characteristics, substantial pilot fuel is required, ranging from 5% to 15% for two-stroke engines and up to 30% for four-stroke engines. This is a significant drawback of ammonia-fueled engines (Maersk, 2022). In developing ammonia engines, unburned ammonia treatment and pilot fuel reduction technology development are key issues that must be addressed (JSTRA, 2022).

In the realm of methanol-fueled engines, two-stroke engines are already more prevalent due to their usage on ships, with some four-stroke engines operating at the TRL 9 stage. Demonstrating the feasibility of retrofitting existing vessels for methanol use, several new methanol vessels are currently on order, promising to significantly expedite commercial development (Oloruntobi et al., 2023). For hydrogen, the four-stroke engine is currently progressing towards the prototype demonstration phase (TRL 7-8) and is approaching the commercialization phase

(TRL 9) (John Snyder, 2020, MAN Energy Solutions, 2023). In contrast, the technical readiness of the two-stroke hydrogen-fueled engine is relatively low. It is expected to be installed in a vessel by 2026, and the demonstration of its operation will take place around 2027 (ClassNK, 2023). While LNG fueled engines has been proven feasible and demonstrated, potential reductions in GHG emissions from LNG fueled ships are discussed in relation to methane emissions (Pavlenko et al., 2020, Balcombe et al., 2021).

For calculating annual fuel consumptions and GHG emissions for the new ships in Table 7-7, the emissions factors and specific fuel consumption data from Table 7-8 were used.

Table 7-8. The specific fuel consumption data and emission factors for estimating annual TtW GHG emissions for selected fuels (Malmgren et al., 2021, IMO, 2020, Kanchiralla et al., 2023)

	Ammonia		LNG			Methanol		Hydrogen	
Lower heating value (MJ/kg)	18.6		49.2			19.9		120	
Engine Types	LSD	MSD	LS-HPDF	LS-LPDF	MS-LPDF	LSD	MSD	LSD	MSD
Main fuel consumption (g/kWh)	349	370	130.6	143.1	152.2	306.3	348	54	58
Pilot fuel consumption (g/kWh)	16.9	17.9	5	2.5	2.6	15.8	18	16.8	18.2
Technical readiness level	5	5	9	9	9	9	9	4	9
Year (applied or expected)	2024	2023-2026	2014	2016	1995	2015	2023	2027	2026-
Emission factor (GHG t/t fuel)									
CO_2	0	0	2.75	2.75	2.75	1.375	1.375	0	0
CH_4	0.000003	0.000003	0.0014	0.017	0.036	0.000006	0.000006	0.000017	0.000017
N_2O	0.0005	0.0005	0.00022	0.00014	0.00013	0.000016	0.000025	0.00033	0.0028
The following emission factors are applied for pilot fuel(MGO/MDO): 3.206 for CO_2 , 0.00006 for CH_4, 0.00015 for N_2O. LSD : Low-speed diesel cycle engines, MSD : Medium-speed diesel cycle engines, LS-HPDF : Low-speed high-pressure dual-fuel engines, LS-LPDF : Low-speed low-pressure dual-fuel engines, MS-LPDF : Medium-speed low-pressure dual-fuel engines									

Utilizing engine technologies with selected alternative fuels presents several technical challenges. In this study, the key future technologies chosen to influence GHG emissions encompass the quantities of pilot fuels for all engines, methane slips for LNG fueled engines, and N_2O emissions for ammonia-fueled engines (JSTRA, 2022). To estimate GHG emissions for the years 2030, 2040, and 2050 when these engines are applied, the assumptions with gradual reductions were adopted, as shown in Table 7-9. The estimation of future-specific fuel consumption resulting from the reduction in pilot fuel, as presented in

Table 7-10, is based on caloric value and assumes a constant engine thermal efficiency More detailed data on gradual reductions are provided in the supplementary material.

Table 7-9. Factors affecting GHG emissions from engine technology development (JSTRA, 2022)

Factors	Fuel and engine type	2030	2040	2050
Pilot fuel (%)	Ammonia fueled engine : LSD	10	5	0
	Ammonia fueled engine : MSD	10	5	0
	LNG fueled engine : LS-HPDF	3.2	1.6	0
	LNG fueled engine : LS-LPDF	1.5	0.75	0
	LNG fueled engine : MS-LPDF	1.5	0.75	0
	Methanol fueled engine : LSD	10	5	0
	Methanol fueled engine : MSD	10	5	0
	Hydrogen fueled engine : LSD	10	5	0
	Hydrogen fueled engine : MSD	10	5	0
Methane slips (CH4 t/t fuel)	LNG fueled engine : LS-HPDF	0.0014	0.0007	0.0002
	LNG fueled engine : LS-LPDF	0.017	0.0085	0.0026
	LNG fueled engine : MS-LPDF	0.036	0.018	0.0054
N_2O slip (N_2O t/t fuel)	Ammonia fueled engine	0.0005	0.00025	0.0000025

Table 7-10. Future specific fuel consumption due to engine technology development

	Ammonia		LNG			Methanol		Hydrogen	
Engine Types	LSD	MSD	LS-HPDF	LS-LPDF	MS-LPDF	LSD	MSD	LSD	MSD

The specific fuel consumption for calculating the annual TtW GHG emissions in 2040									
Main fuel consumption (g/kWh)	368.4	390.5	132.8	144.2	153.3	323.2	367.3	57.0	61.3
Pilot fuel consumption (g/kWh)	8.4	9.0	2.5	1.3	1.3	7.9	9.0	8.4	9.1
The specific fuel consumption for calculating the annual TtW GHG emissions in 2050									
Main fuel consumption (g/kWh)	387.8	411.1	134.9	145.3	154.5	340.2	386.6	59.98	64.48

ii. Energy efficiency improvement through energy-saving technologies

The implementation of energy-saving technologies presents an effective means to mitigate GHG emissions from ships(Jimenez et al., 2022). This study focuses on pinpointing such technologies for reducing GHG emissions. However, it excludes alternative fuels and speed reduction techniques, which are covered in other sections of this study. Table 7-11 indicates the CO_2 reduction potential (in percentages of αj) for each respective technology spanning from 2030 to 2050. These potentials were determined by examining not only each fuel reduction rate but also the rate at which ships adopted the given technology relative to the entire fleet, with 54% for 2030 and 100% for 2050 (IMO, 2020). More detailed data are provided in the supplementary material. It's worth noting that these energy efficiency models predominantly influence a ship's fuel consumption. Consequently, any reduction in fuel consumption directly correlates with the CO_2 reduction attributable to the associated energy-saving technology (Yan et al., 2023).

Table 7-11. Selected energy saving technologies and their CO_2 reduction potential(αj %) compared to base year

	Selected technologies	2030	2040	2050
1	Propeller maintenance	2.20%	3.08%	3.95%
2	Hull maintenance	2.22%	3.06%	3.90%
3	Optimization water flow hull openings	1.64%	2.32%	3%
4	Hull coating	1.48%	2.02%	2.55%
5	Propeller improvements	1.40%	1.90%	2.40%

6	Air lubrication	1.35%	1.81%	2.26%
7	Steam plant improvements	1.30%	1.72%	2.13%
8	Main engine improvements	0.25%	0.35%	0.45%
9	Reduced auxiliary power usage	0.40%	0.56%	0.71%
10	Auxiliary systems	0.87%	1.23%	1.59%
11	Wind power	0.89%	1.28%	1.66%
12	Super light ship	0.28%	0.34%	0.39%
13	Waste heat recovery	1.68%	2.39%	3.09%
14	Solar panels	0.18%	0.24%	0.30%

7.2.4. TtW GHG emissions and average GHG intensity for selected fuel

To estimate the annual GHG emissions from onboard ships, data on fuel consumption and GHG emission factors are collected. The following equation is utilized to compute both the annual GHG emissions from ships and the average GHG intensity of the fuel, utilizing emission factors from Table 7-8. For e fuels produced from captured carbon from atmosphere (CO2_DAC), the CO_2 emission factor(Cf_{CO2}) is considered zero for TtW GHG emission calculations.

- $E = \sum_{i}^{n\ fuel} \sum_{j}^{m\ engine} FC_{i,j} \times EF_{GHG}$ (7-18)

- $EF_{GHG} = Cf_{CO2} + Cf_{CH4} \times GWP_{CH4} + Cf_{N2O} \times GWP_{N2O}$ (7-19)

- $GHG_{I} = \frac{E}{\sum_{i}^{n\ fuel} \sum_{j}^{m\ engine} FC_{i,j} \times LHV_{i}}$ (7-20)

where; E: Estimated annual GHG emission amount (t), $FC_{i,j}$: Fuel consumption for fuel type i in engines j (t fuel) of ships, EF_{GHG}: GHG emission factor (t/t fuel) corresponding to each fuel, Cf_{CO2}: the CO_2 emission factor (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, which is 28 for a 100-year time horizon, GWP_{N2O}: Global warming potential for N_2O, which is 265 for a 100-year time horizon, and LHV : Lower heating value of $fuel_i$

For the quantification of GHG emissions from the entire fleet in the base year as well as in the projected years (2030, 2040, and 2050), the following equation was employed to compute the aggregate TtW GHG emissions upon the prospective introduction of e-fuels in a specified future year.

- $E_{\mathrm{year}} = \sum_{\mathrm{i}}^{\mathrm{SN\ base\ year}} \sum_{\mathrm{k}}^{\mathrm{m\ engine}} \mathrm{FC}_{\mathrm{HFO,i,k}} \times \mathrm{EF}_{\mathrm{GHG}} + \sum_{\mathrm{i}}^{\mathrm{SN\ transport\ demand}} \sum_{\mathrm{j}}^{\mathrm{n\ fuel}} \sum_{\mathrm{k}}^{\mathrm{m\ engine}} \mathrm{FC}_{\mathrm{i,j,k}} \times \mathrm{EF}_{\mathrm{GHG}} + \sum_{\mathrm{i}}^{\mathrm{SN\ speed\ reduction}} \sum_{\mathrm{j}}^{\mathrm{n\ fuel}} \sum_{\mathrm{k}}^{\mathrm{m\ engine}} \mathrm{FC}_{\mathrm{i,j,k}} \times \mathrm{EF}_{\mathrm{GHG}} - E_{\mathrm{scrapping}}$ (7-21)
- $E_{\mathrm{scrapping}} = \sum_{\mathrm{i}}^{\mathrm{SN\ Scapping}} \sum_{\mathrm{k}}^{\mathrm{m\ engine}} \mathrm{FC}_{\mathrm{HFO,i,k}} - \sum_{\mathrm{i}}^{\mathrm{SN\ scrapping}} \sum_{\mathrm{j}}^{\mathrm{n\ fuel}} \sum_{\mathrm{k}}^{\mathrm{m\ engine}} \mathrm{FC}_{\mathrm{i,j,k}} \times \mathrm{EF}_{\mathrm{GHG}}$ (7-22)
- $\mathrm{TE}_{\mathrm{year}} = E_{\mathrm{year}} \times \sum_{\mathrm{i}}^{\mathrm{j}} \alpha j_{\ year}$ (7-23)

Where, αj year : CO_2 reduction potential (in percentages of αj) for energy saving technology

7.3 Analysis results

7.3.1 Comparison of WtT GHG emissions

Figure 7-5 shows results of a detailed analysis of WtT emissions of e-fuels selected under the consideration of 2022 year when the grid mix electricity was revealed to produce 560 gCO_2 eq./kWh. For Hydrogen, the PEM electrolysis pathway was found as the highest WtT emissions, reaching 281.73 gCO_2 eq./MJ. In contrast, the ALK pathway yielded relatively lower emissions at 258.35 gCO_2 eq./MJ. Notably, these methods claim 2-3 times greater than the average WtT emissions of 97.6 gCO_2 eq./MJ for hydrogen when produced by naphtha cracking and steam methane reforming. For both LNG and Methanol, the PEM-DAC pathways were revealed to produce the highest levels of emissions, with values of 372.78 and 393.95 gCO_2 eq./MJ respectively, primarily due to the energy-intensive nature of direct air capture used to obtain CO_2. Conversely, the ALK-PSA pathway demonstrated the lowest emissions at 307.05 gCO_2 eq./MJ for LNG and 304.77 gCO_2 eq./MJ for Methanol. Ammonia produced via the PEM-Cryo method led to the highest emissions at 300.72 gCO_2 eq./MJ, whereas the ALK-Cryo process was found the most clean method with 273.87 gCO_2 eq./MJ. Importantly, this finding shows that hydrogen production using grid-mixed electricity would not be a promising solution, compared to any other feedstocks, such as CO_2 and N_2.

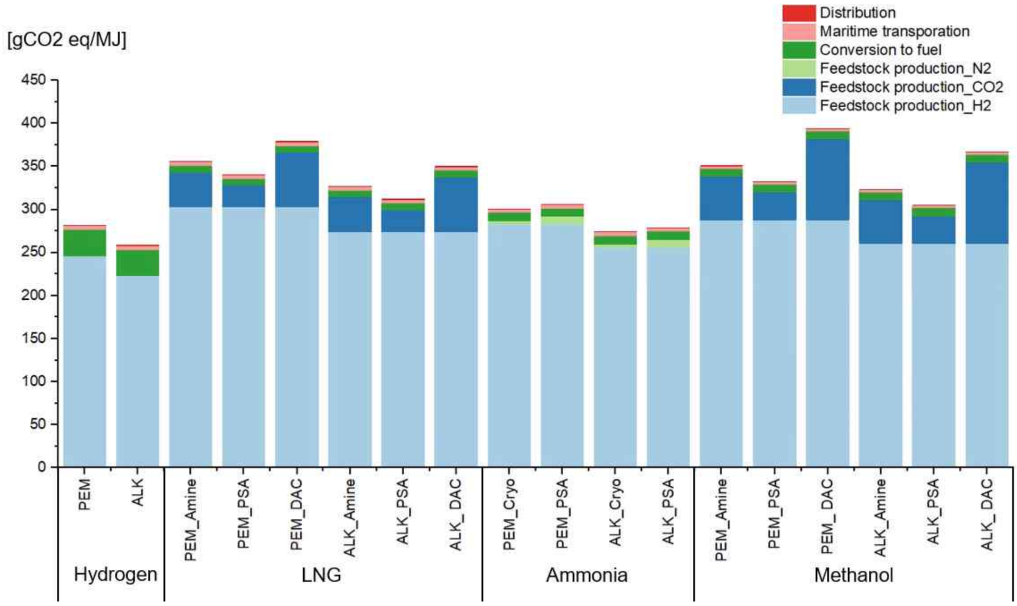


Figure 7-5 WtT emissions with grid's mixed electricity based on selected fuel production pathways in the base year (2022)

Figure 7-5 illustrates the reductions in GHG emission levels pertinent to e-fuel productions during the upcoming decades: 2030, 2040, and 2050. These predictions are based on assumptions on that the grid mix electricity would lead to reductions in GHG emissions to 200, 140, and 80 gCO_2 eq./kWh in the respective years by the technical innovation as discussed in Table 7-2. The graph effectively captures the consequent decline in GHGs as a result of these reductions. Nevertheless, it's crucial that the WtT emissions of e-fuels were predicted far greater than those of some conventional fossil fuels. For example, the WtT emissions from LNG and methanol using the 2050 grid mix electricity remain higher than those of their conventional counterparts, which would emit 18.1 and 31.2 gCO_2 eq./MJ (as highlighted in the graph), respectively. In contrast, while conventional hydrogen and ammonia production emit relatively high levels of GHGs at 97.6 and 151.7 gCO_2 eq./MJ (as highlighted in the graph), these emissions are marked still lower than those produced by the e-fuel methods if the grid mix electricity applied. This disparity underscores the ongoing challenges in e-fuel production as electricity grids evolve towards more sustainable sources. While the 2022 GHG emissions for Hydrogen via the PEM and ALK pathways were marked at 281.73 and 258.35 gCO_2 eq./MJ respectively, by 2050 these values plummeted to 35.77 and 33.87 gCO_2 eq./MJ. Similar trends were observed for LNG, with PEM-DAC emissions dropping from 372.78 gCO_2 eq./MJ in 2022 to 49.45 gCO_2 eq./MJ by 2050. The ALK-PSA method is also subject to decrease from 307.05 gCO2 eq./MJ in 2022 to 44.19 gCO2 eq./MJ by 2050. For Ammonia emissions associated with PEM-Cryo descended from 300.72 in 2022 to 38.11 by 2050, and ALK-Cryo reduced from 273.87 gCO2 eq./MJ in 2022 to 35.21 gCO_2 eq./MJ in 2050. Lastly, Methanol emissions via the PEM-DAC pathway would decrease from 393.95 gCO_2 eq./MJ in 2022 to 43.03 gCO_2 eq./MJ in 2050, while the ALK-PSA pathway witnessed a decline from 304.77 gCO_2 eq./MJ in 2022 to 43.72 gCO_2 eq./MJ by 2050.

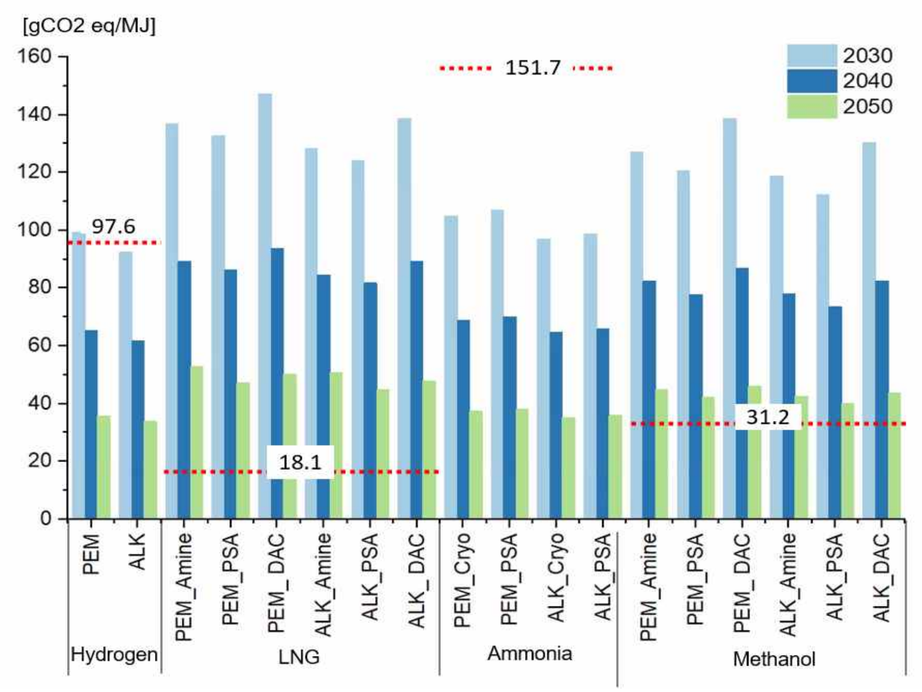


Figure 7-6 WtT emissions with grid's mixed electricity based on selected fuel production pathways in the future (in 2030, 2040 and 2050)

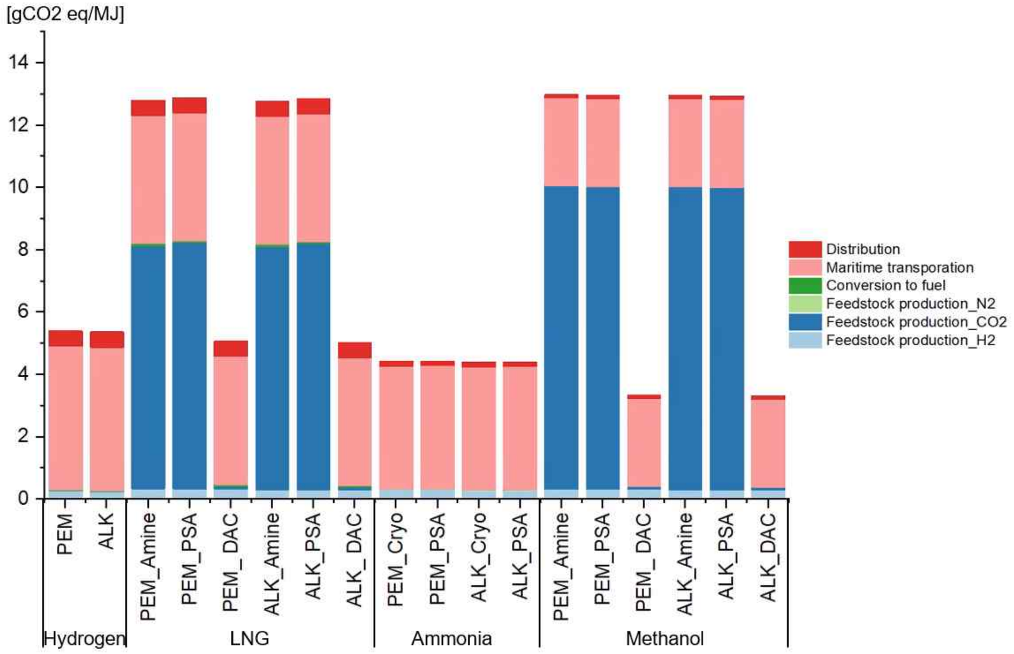


Figure 7-7 WtT emissions based on selected fuel production pathway using wind power in base year (2022)

Figure 7-7 presents results of WtT analysis in 2022, assuming a carbon intensity of 0.62 gCO$_2$eq./kWh when using wind-induced electricity. Emissions for hydrogen production both through PEM and ALK pathways were notably marked lower than those in the grid mix scenario. Specifically, the PEM process results in emissions of 0.27 gCO$_2$ eq./MJ, whereas the ALK process registers 0.25 gCO$_2$ eq./MJ for H2 feedstock production. Ammonia production through the PEM-Cryo and ALK-Cryo processes would be found at 0.31 and 0.28 gCO$_2$ eq./MJ, respectively, for H2 feedstock production. The GHG emissions of hydrogen production for all selected fuels are at a similar level, ranging from 0.25 to 0.34 gCO$_2$ eq./MJ. In the case of LNG and methanol, the PEM-Amine, PEM-PSA, ALK-Amine, and ALK-PSA pathways would yield emissions ranging from7.81 and 9.71 gCO$_2$ eq./MJ, respectively, for CO$_2$ feedstock production.

A key observation from Figure 7-7 is the significance on the level of emissions attributed to maritime transportation. For instance, with hydrogen produced via the PEM pathway, maritime transportation contributes 4.60 gCO$_2$ eq./MJ to the total WtW emission of 5.40 gCO$_2$ eq./MJ, accounting for roughly 85% of the total emissions when utilizing a liquefied hydrogen carrier powered by conventional fuels.

The high WtT emissions in the production of CO_2 feedstock for LNG and Methanol through pathways like PEM_Amine, PEM_PSA, ALK_Amine, and ALK_PSA can be attributed to the study's assumption of importing CO_2 using a liquefied CO_2 carrier from South Korea to Australia. It should be emphasized that if the CO_2 is domestically sourced rather than imported, the GHG emissions associated with the CO_2 carrier would be negligibly small. Considering the LNG fuel produced via the PEM_Amine pathway, maritime transportation account for 4.11 g CO_2 eq./MJ, while CO_2 feedstock would add extra 7.62 gCO_2 eq./MJ. This totals nearly 90% of the 12.68 CO_2 eq./MJ emissions. See the details in the supplementary material. This underlines the considerable impact of maritime transport on WtT emissions, especially in scenarios mirroring situations in regions like South Korea where there's a heavy reliance on importing resources via maritime transport. Consequently, even with the adoption of sustainable energy sources like wind power for e-fuel production, the emission levels from maritime transportation still remain as a substantial concern, especially if international shipping fail to achieve in-time decarbonization. These findings underline the urgency for innovative strategies to reduce emissions in the transport sector, notably when sourcing e-fuels from abroad. In contrast to the emissions associated with the grid mix electricity, these findings highlight the paramount environmental benefits of leveraging wind power in e-fuel production, while also pointing to areas, like maritime transport, where further improvements are imperative.

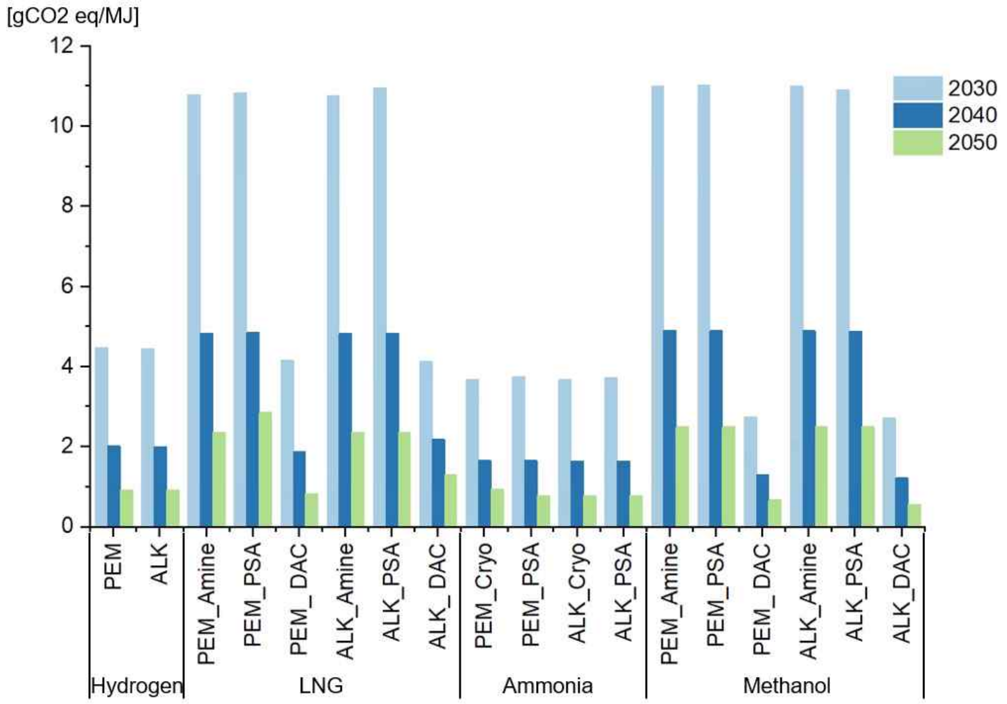


Figure 7-8 WtT emissions based on selected fuel production pathway using wind power in the future (2030, 2040 and 2050)

Figure 7-8 reveals the trajectory of WtT emissions associated with the subject fuel production pathways when leveraging wind power, spanning across the years of 2030, 2040, and 2050. In particular, the analysis results delineates a pronounced and consistent reduction in emissions for all fuels - hydrogen, LNG, ammonia, and methanol - irrespective of their production pathways. This observation accentuates the importance of wind power having transformative potential as a sustainable energy source for e-fuel production. The depicted trends both confirm the environmental benefits of switching to wind-powered e-fuel production and highlight the need for further technological and infrastructural progress to meet global decarbonization goals.

In addition, when utilizing solar power (PV) with a carbon intensity of 6.15 g CO2eq./kWh for electricity production (Marashli et al., 2022), the overall trends in WtT emissions for the subject fuels are similar to those of wind power as shown in Figure 7-7 and Figure 7-8 . Overall, the WtT emissions of different fuel types are projected to decrease over time, with the greatest reductions expected for hydrogen and ammonia production using renewable energy sources. By 2050, the WtT emissions of hydrogen and ammonia production using solar power (PV) and wind power are projected to be less than 1 gCO_2eq./MJ. More details on the WtT emissions for the selected fuels using solar power can be found in the supplementary material.

7.3.2 Comparison of TtW GHG emissions

Table 7-12 shows the annual fuel consumptions for the subject fuels for main and auxiliary engines used in the calculation of TtW GHG emissions, using ship specification of the new ships in Table 7-5. Notably, the fuel mass consumptions for methanol and ammonia engines significantly exceeds those of HFO, LNG, and hydrogen engines, primarily due to the differences in their energy densities.

Table 7-12 Annual fuel consumptions(ton) depending on selected fuels

Ship size (DWT)	– 200,000					200,000 - +				
Fuel types	Main engine		Aux engine		Total	Main engine		Aux engine		Total
	Main fuel	Pilot fuel	Main fuel	Pilot fuel		Main fuel	Pilot fuel	Main fuel	Pilot fuel	
Ammonia	21282	1031	890	43	23245	30120	1459	939	45	32563
LNG:LS-HPDF	7964	305	366	6	8641	11271	432	386	7	12096
LNG : LS-LPDF	8726	152	366	6	9251	12350	216	386	7	12959
Methanol	18678	963	837	46	20524	26434	1364	883	46	28727
Hydrogen	3293	1024	139	46	4503	4660	1450	137	46	6294
HFO	9726	-	469	-	10195	13765	-	495		14260

Figure 7-9 illustrates the annual GHG emissions, which reflect technological improvements as detailed in Table 7-9 and

Table 7-10, for a ship with a deadweight tonnage (DWT) of less than 20,000 across the base year, and the years 2030, 2040, and 2050, using the six fuel types, as outlined in Table 7-5. Although methanol and LNG have identical fuel consumption rates, their associated GHG emissions are determined by the carbon source: DAC, denoting CO2 captured directly from the air, and Fossil, indicating CO_2 captured from industrial sources of fossil fuel emissions. The analysis highlights the potential for emissions reductions achievable with ammonia and hydrogen, alongside e-methanol and e-LNG utilizing DAC. These reductions are compared not only to those of HFO but also to LNG and methanol derived from Fossil sources. For instance, in the base year, the ship fueled by HFO exhibited the highest annual GHG emissions at 32,515t, while the e-LNG-powered ship equipped with LS-HPDF had the lowest emissions at 2,173t. The TtW GHG emission of LNG LS-HPDF was observed to be somewhat more influenced by the pilot fuel than that of LS-LPDF. This difference can be attributed to the higher pilot fuel consumption in LNG LS-HPDF having a diesel combustion cycle, compared to LS-LPDF with an Otto combustion cycle, even though both options use the same LNG fuel.

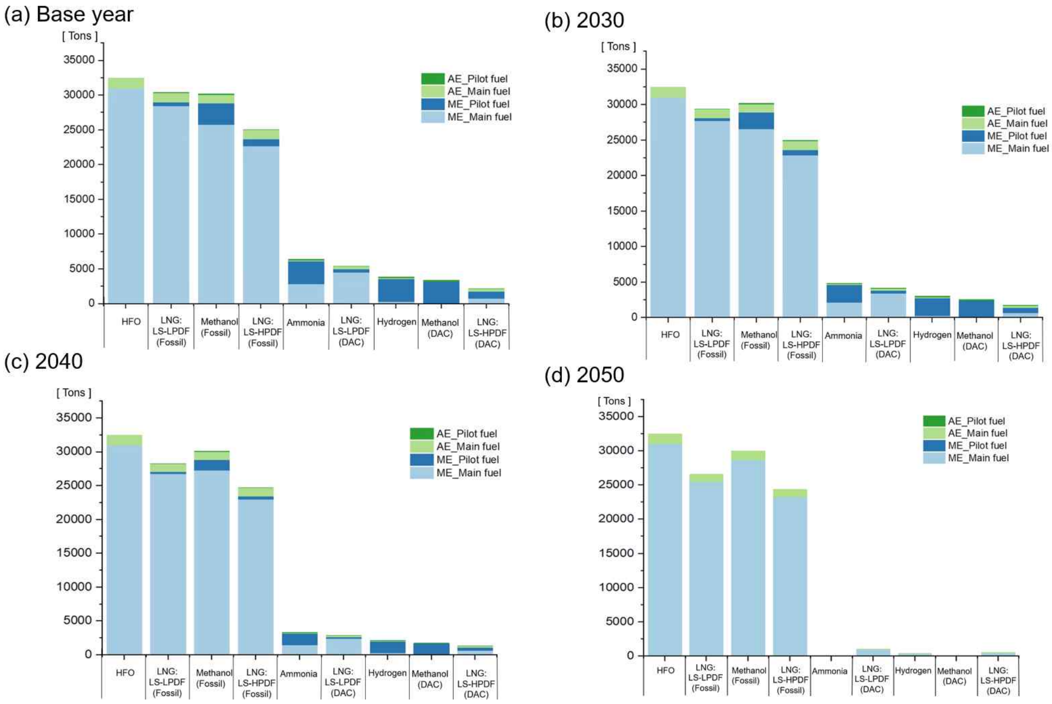


Figure 7-9 The annual GHG emissions depending on six selected fuels : (a) Base year, (b) 2030, (c) 2040 and (d) 2050

Notably, the TtW GHG emissions of e-fuels, such as e-methanol and e-LNG, produced from captured carbon through DAC were significantly lower. This is because the CO_2 emissions, even though they occur at the point of combustion, are offset because they originated from the atmosphere. In the case of LNG LS LPDF engines with DAC, they generate annual GHG emissions exceeding 5,000 tons, even when CO_2 emissions from the main engine are excluded. A substantial portion of these emissions is attributed to methane slip, highlighting the necessity of minimizing methane slip to move toward achieving net-zero emissions for LNG engines.

Throughout the evaluated years - the base year, 2030, 2040, and 2050 - alternative fuels such as e-ammonia, e-hydrogen, and e-methanol would contribute to relatively low direct fossil fuel emissions. However, when considering the use of significant quantities of fossil fuel-based pilot fuels, these alternatives account for at least 50% of the total GHG emissions compared to other fuels. As illustrated in Figure 7-9 (d), advancements in engine technology are projected to play a substantial role in reducing TtW GHG emissions, particularly in the 2050 scenario that assumes the elimination of pilot fuel use. For vessels utilizing such fuels, transitioning from conventional pilot fuels to carbon-neutral alternatives, including biofuels, represents a viable strategy to further curtail GHG emissions. Nonetheless, it is critical to highlight that ammonia, despite being a carbon-free fuel, could contribute significantly to overall GHG emissions due to the production of N_2O during combustion. Therefore, technological improvements to mitigate the impact of this chemical are essential for achieving sustainability in the near future.

Fuel type	Carbon source	Ship Capacity (-199,999)			Ship Capacity (200,000-)		
		Main fuel	Pilot fuel	Total	Main fuel	Pilot fuel	Total
Base year							
HFO	-	79.3	-	79.3	79.3	-	79.3
Methanol	CO2_Fossil	69.3	76.1	70.0	69.3	76.1	70.0
LNG : LS-HPDF	CO2_Fossil	58.7	76.1	59.3	58.5	76.1	59.1
LNG : LS-LPDF	CO2_Fossil	66.8	76.1	66.9	66.7	76.1	66.8
Methanol	CO2_DAC	0.2	76.1	7.8	0.2	76.1	7.8
LNG : LS-HPDF	CO2_DAC	2.8	76.1	5.1	2.6	76.1	4.9
LNG : LS-LPDF	CO2_DAC	10.9	76.1	11.9	10.8	76.1	11.8
Ammonia	-	7.1	76.1	14.0	7.1	76.1	14.0
Hydrogen	-	1.0	76.1	8.5	0.9	76.1	8.4
2030							
HFO	Fossil	79.3	-	79.3	79.3	-	79.3
Methanol	CO2_Fossil	69.3	76.1	69.8	69.3	76.1	69.8

LNG : LS-HPDF	CO2_Fossil	58.3	76.1	58.7	58.1	76.1	58.6
LNG : LS-LPDF	CO2_Fossil	64.2	76.1	64.3	64.1	76.1	64.3
Methanol	CO2_DAC	0.2	76.1	5.9	0.2	76.1	5.9
LNG : LS-HPDF	CO2_DAC	2.4	76.1	4.1	2.2	76.1	4.0
LNG : LS-LPDF	CO2_DAC	8.3	76.1	9.1	8.2	76.1	9.0
Ammonia	-	5.3	76.1	10.7	5.3	76.1	10.7
Hydrogen	-	1.0	76.1	6.6	0.9	76.1	6.5
2040							
HFO	Fossil	79.3	-	79.3	0.0	-	79.3
Methanol	CO2_Fossil	69.3	76.1	69.7	69.3	76.1	69.7
LNG : LS-HPDF	CO2_Fossil	57.9	76.1	58.2	57.8	76.1	58.1
LNG : LS-LPDF	CO2_Fossil	61.7	76.1	61.8	61.6	76.1	61.7
Methanol	CO2_DAC	0.2	76.1	4.0	0.2	76.1	4.0
LNG : LS-HPDF	CO2_DAC	2.0	76.1	3.1	1.9	76.1	3.0
LNG : LS-LPDF	CO2_DAC	5.8	76.1	6.3	5.7	76.1	6.3
Ammonia	-	3.6	76.1	7.2	3.6	76.1	7.2
Hydrogen	-	1.0	76.1	4.7	0.9	76.1	4.7
2050							
HFO	Fossil	79.3	-	79.3	79.3	-	79.3
Methanol	CO2_Fossil	69.3	-	69.3	69.3	-	69.3
LNG : LS-HPDF	CO2_Fossil	57.3	-	57.3	57.3	-	57.3
LNG : LS-LPDF	CO2_Fossil	58.1	-	58.1	58.1	-	58.1
Methanol	CO2_DAC	0.2	-	0.2	0.2	-	0.2
LNG : LS-HPDF	CO2_DAC	1.4	-	1.4	1.4	-	1.4
LNG : LS-LPDF	CO2_DAC	2.3	-	2.3	2.2	-	2.2
Ammonia	-	0.04	-	0.04	0.04	-	0.04
Hydrogen	-	1.0	-	1.0	0.9	-	0.9

Table 7-13 Average GHG intensity (CO_2 eq./MJ) of the energy used on board ships based on technologies improvement in the base year and the future (2030,2040 and 2050)

Table 7-13 compares the average GHG intensities of ships using main fuels and pilot fuels for engines. The average GHG intensities shown in Table 7-13 have similar characteristics to the annual GHG emission results shown in Figure 7-9. The average GHG intensity values of ships above and below 20,000 DWT are almost same in trend, which means that the ship capacities have a remarkable impact on the total annual GHG emissions, but not on the average GHG intensities.

7.3.3 Comparison of WtW GHG emissions

Figure 7-10 and Figure 7-11 illustrate the WtW GHG intensities for various fuels when produced using mixed grid electricity and off-grid renewable energy sources, respectively, across four-time frames: the base year, 2030, 2040, and 2050.

Figure 7-10 reveals a general trend of decreasing GHG intensity for all fuels over time. This trend reflects the anticipated improvements in grid electricity's GHG intensity, as the energy mix becomes greener due to technological advances, as discussed in Sections 7.2.2 and 7.2.3. It is noteworthy that a significant proportion of GHG emissions are attributed to WtT processes, especially in the production of e-fuels such as e-methanol and e-LNG, which demonstrate a significant reduction in WtT emissions over the years when utilizing DAC technology. Meanwhile, when methanol and LNG are produced from fossil-based carbon sources, their emissions reduction compared to conventional HFO, with a baseline of 90.3 CO_2 eq./MJ, were relatively insignificant. Within the mixed grid context, methanol and LNG also present higher WtW GHG intensities than ammonia and hydrogen, emphasizing the importance of carbon source selection.

Conversely, Figure 7-11 also shows that integrating renewable energy leads to substantially lower GHG intensities across all years in comparison to the mixed grid scenario. As the GHG intensity of electricity from renewable sources decreases, the emission gaps between renewable fuels narrows substantially, indicating a convergence towards lower emission profiles.

Analysis results from both figures insist the need of an innovation in fuel technology and energy production by 2050. With the shipping industry's GHG emissions reduction targets in mind, these figures provide stakeholders with insights into the most viable fuel production pathways. They underscore that the decarbonization potential for each fuel type is largely determined by upstream processes, such as the energy sources used for fuel production and conversion.

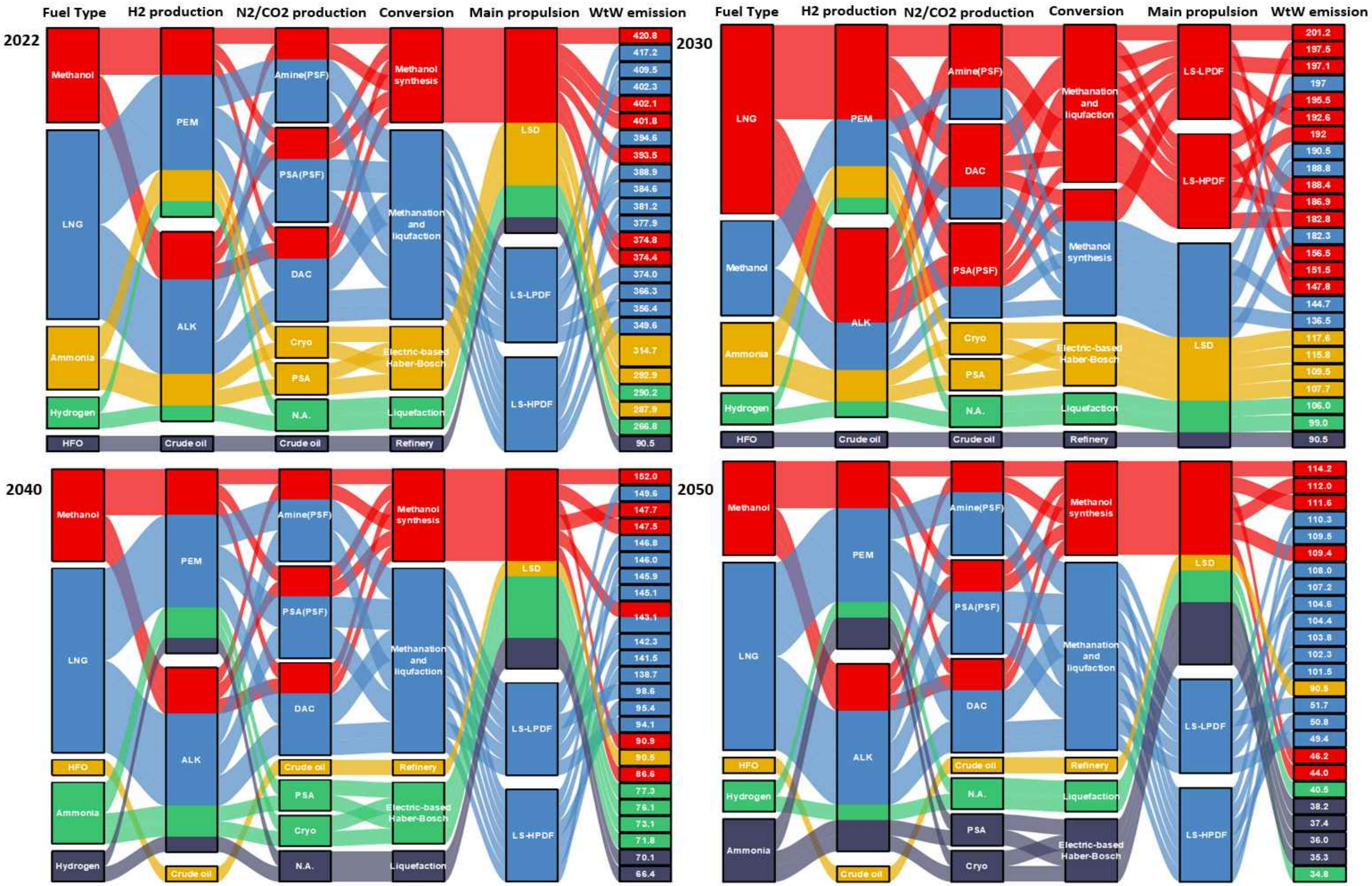


Figure 7-10 WtW GHG intensity depending on fuel production pathways using the grid's mixed electricity in base year, 2030, 2040 and 2050

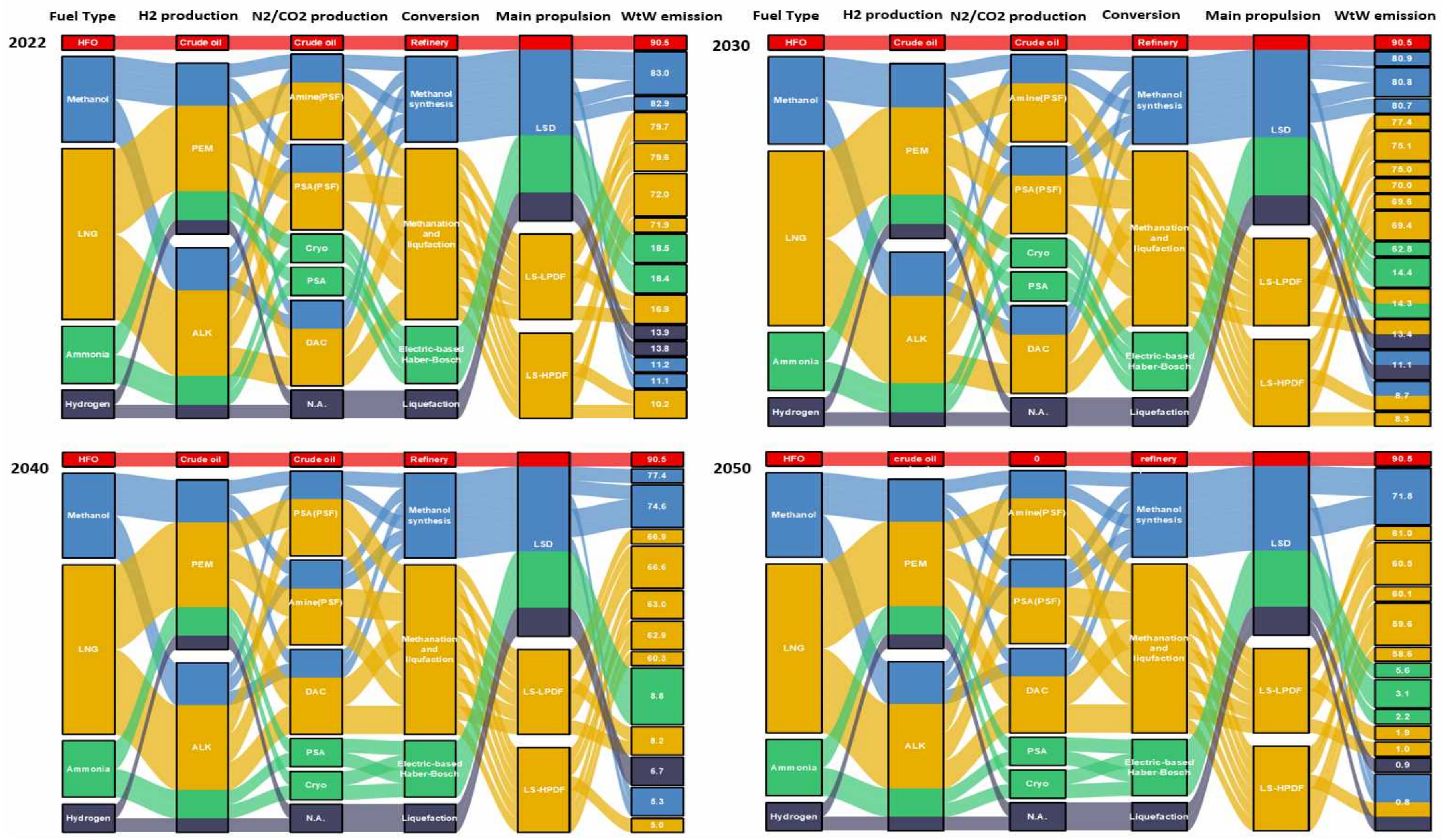


Figure 7-11 WtW GHG intensity depending on fuel production pathways using off grid (Windfarm) from renewable energy sources in base year, 2030, 2040 and 2050

Figure 7-12 illustrates the ratio of GHG emissions between WtT and TtW part. A notable observation is that as the GHG intensity of electricity generation decreases, the WtT proportion correspondingly diminishes. Furthermore, ammonia, hydrogen, methanol, and LNG fuels produced via DAC were marked as great portions of WtT GHG emissions.

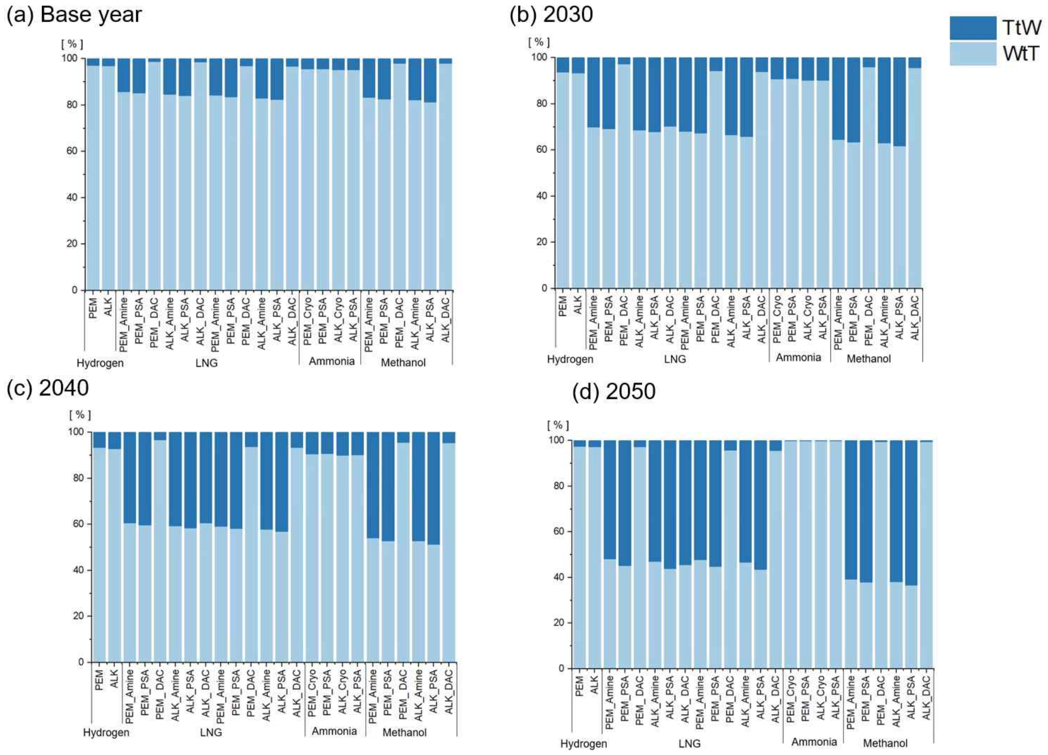


Figure 7-12 Ratio of GHG emissions between WtT and TtW emissions using the grid's mixed electricity

7.3.4 GHG reduction potential of the emissions from total fleet using selected fuels

Figure 7-13 compares the annual GHG emissions of the selected fleet using various fossil-based fuels (HFO, LNG: LS-LPDF, Methanol, and LNG: LS-HPDF) with the emissions from using hydrogen-based e-fuels (Ammonia, Hydrogen, and others). This comparison is made under two transport demand scenarios—low growth and high growth—and takes into account technological advancements expected in 2030, 2040, and 2050, with the assumption that all new vessels added to the fleet will utilize each of the selected fuel options. For detailed data on the number of new vessels, please refer to the supplementary information.

The overall results delineate a different trend between fossil-based fuels and those derived from renewable e-fuels. Fossil-based fuels, represented by HFO, LNG (LS-LPDF and LS-HPDF), and Methanol, are shown to perpetuate an upward trend in emissions in high growth scenarios, with HFO emissions soaring to 128,296,873 metric tons by 2050. LNG as LS-LPDF and Methanol also exhibit a concerning rise, although with a temporary plateau or slight decrease for LNG: LS-LPDF post-2040. The emissions from vessels using LNG: LS-HPDF under the same scenario ascend steadily, culminating at 98,546,538 metric tons in 2050.

In stark contrast, e-fuels such as Ammonia and Hydrogen, produced from renewable sources, emerge as the harbingers of a declining emissions trajectory, even under scenarios of high transport demand. By 2050, Ammonia and Hydrogen are posited to reduce emissions to 9,980,982 and 11,402,291 metric tons, respectively, showcasing their excellence in environment. Similarly, renewable variants of Methanol and LNG: LS-HPDF demonstrate a remarkable emissions descent, aligning with the overarching trend observed in the use of e-fuels.

This divergence in emissions patterns underscores the profound implications of fuel selection on the future sustainability of international shipping. The comparative analysis reveals that renewable e-fuels stand as a transformative force, capable of mitigating the climate impact even amidst high growth scenarios. As the maritime industry charts its course towards a lower carbon footprint, the transition to renewable e-fuels presents not only an environmental imperative but also a strategic direction for industry stakeholders. The findings of this study thereby emphasize the urgency of integrating renewable e-fuels into the marine fuel mix, to steer the global fleet towards decarbonization.

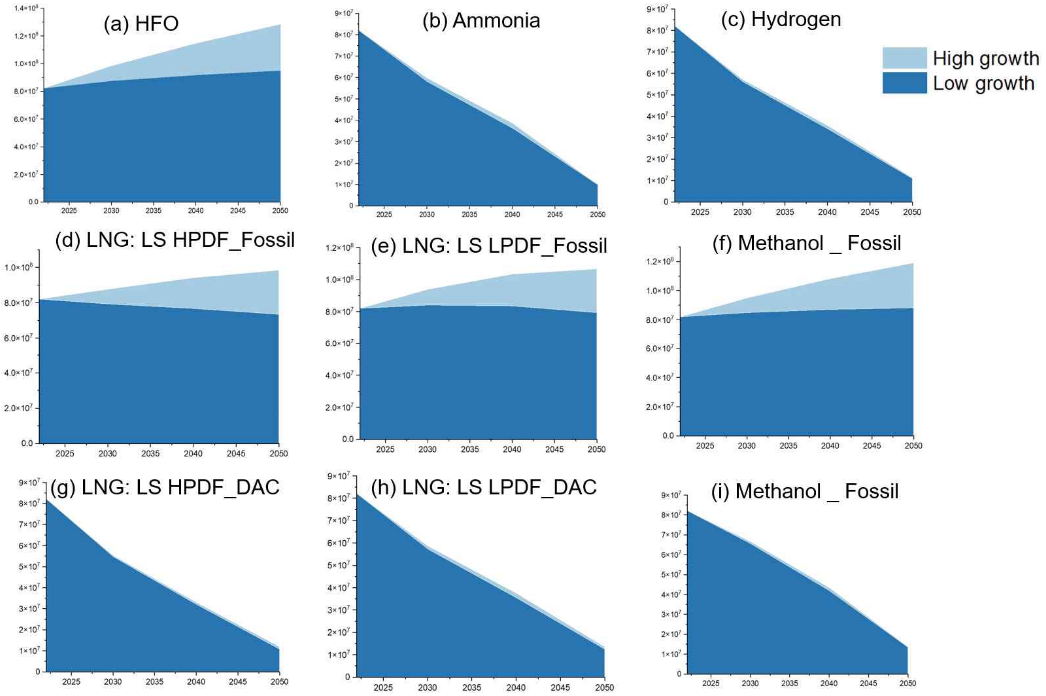


Figure 7-13 Annual GHG emissions of a fleet using fossil based fuels and hydrogen based e fuels

7.3.5 The relationship between TtW GHG emissions and carbon intensity

Figure 7-14 illustrates variations in carbon intensity values under different future transport demand scenarios, namely high growth, and low growth. Interestingly, the high growth scenario has a lower carbon intensity than the low growth scenario. As explained in Section 7.3.4, even though the high growth scenario leads to higher annual TtW GHG emissions, the average carbon intensity across all fuel types decreases slightly. In contrast, HFO's carbon intensity remains constant in both scenarios. This reduction is due to the increased use of alternative fuels in the fleet. Even with a significant increase in transport demand, strategically using alternative fuels can improve energy efficiency and decarbonize the fleet more effectively than simply increasing the number of ships.

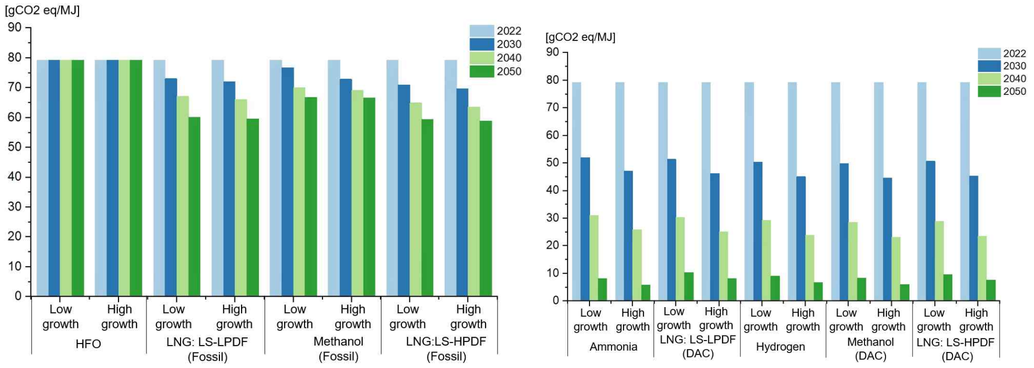


Figure 7-14 Carbon intensity(gCO$_2$ eq./MJ) of the fleet : (a) fossil based fuels, (b) hydrogen based e fuels

7.4 Chapter summary and conclusions

The key findings from this chapter and its conclusions are as follows:

- The study demonstrates significant variations in WtT and TtW GHG emissions among different marine fuels, highlighting the crucial role of clean electricity and technological advancements in reducing emissions from e-fuels by 2050. Particularly, PEM electrolysis and PEM-DAC pathways for hydrogen and LNG/methanol production show the highest emissions, emphasizing the need for renewable energy integration.

- Renewable e-fuels, such as ammonia and hydrogen, produced through environmentally sustainable methods, are identified as having substantial potential to lower GHG emissions in maritime transportation. The transition towards these e-fuels, coupled with advancements in engine technology and the adoption of carbon-neutral pilot fuels, is critical for achieving significant reductions in GHG emissions.

- The comparative analysis between fossil-based fuels and hydrogen-based e-fuels up to 2050 reveals a stark contrast in emissions trajectories, with e-fuels offering a promising path to mitigate environmental impacts even under scenarios of increased transport demand. This underscores the transformative potential of renewable e-fuels in decarbonizing the maritime sector.

- The relationship between TtW GHG emissions and carbon intensity under different future transport demand scenarios indicates that strategic deployment of alternative fuels can lead to improved energy efficiency and more effective decarbonization, even with heightened transport demand. This finding highlights the effectiveness of alternative fuels in enhancing the environmental performance of maritime transport.

- Overall, the research underscores the importance of establishing robust default WtW emission values and the need for comprehensive LCA guidelines that incorporate regional or geographic characteristics, fuel production technologies, and voyage distances. These insights are crucial for developing unique default LCA values for each country, thereby improving the accuracy and precision of holistic environmental assessments in the maritime sector. The study also points to the potential enhancement of decision/policy-making processes, through the integration of these findings, contributing to more effective emission control measures in the transportation sector.

8 DEVELOPING A FRAMEWORK FOR EFFECTIVE ACCOUNTING GHG EMISSIONS FROM INTERNATIONAL SHIPPING FOR SUSTAINABLE MARINE FUEL AND ONBOARD CARBON CAPTURE: CASE STUDY OF METHANOL

8.1 Introduction

The urgent need to decarbonize the international shipping industry is a critical component in the global effort to mitigate climate change. In pursuit of this goal, the industry has undertaken initiatives including enhancing ship efficiency, adopting alternative fuels, and implementing onboard carbon capture systems (OCCS). However, a significant challenge within the current regulatory framework is the inadequate differentiation in emission accounting between carbon-neutral, sustainable renewable fuels and traditional fossil fuels. This often leads to an overestimation of emissions from renewable sources, thereby distorting the true carbon footprint of the shipping sector. Compounding this issue is the absence of uniform guidelines for accounting CO_2 emissions in shipping, which hinders the development of effective regulatory policies for carbon emission control.

To achieve genuine decarbonization in international shipping, it is essential not only to discourage further extraction of fossil fuels but also to promote effective carbon capture technologies that ensure permanent carbon sequestration. This study addresses a pivotal research question: How can regulatory accounting methods be refined to more accurately reflect GHG emissions in international shipping, especially from sustainable renewable fuels? Additionally, it explores how onboard carbon capture systems can be seamlessly integrated into the GHG accounting framework to ensure that captured carbon is accurately accounted for without the risk of double-counting.

8.2 Case study

This study focused on developing a life cycle thinking-based accounting framework GHG emission to support 1) the uptake of the most sustainable marine fuels and introduction of OCCS for international shipping community, 2) the use of life cycle assessments to evaluate the sustainability of ship fuels, and 3) the implementation of a consistent and transparent approach to emissions reporting. Ultimately, the goal of this methodology is to provide a clear and accurate picture of the progress being made in reducing emissions from the shipping sector, and to support efforts to achieve the ambitious target of net-zero emissions in the industry by 2050. Figure 8-1 shows the methodology applied in this study.

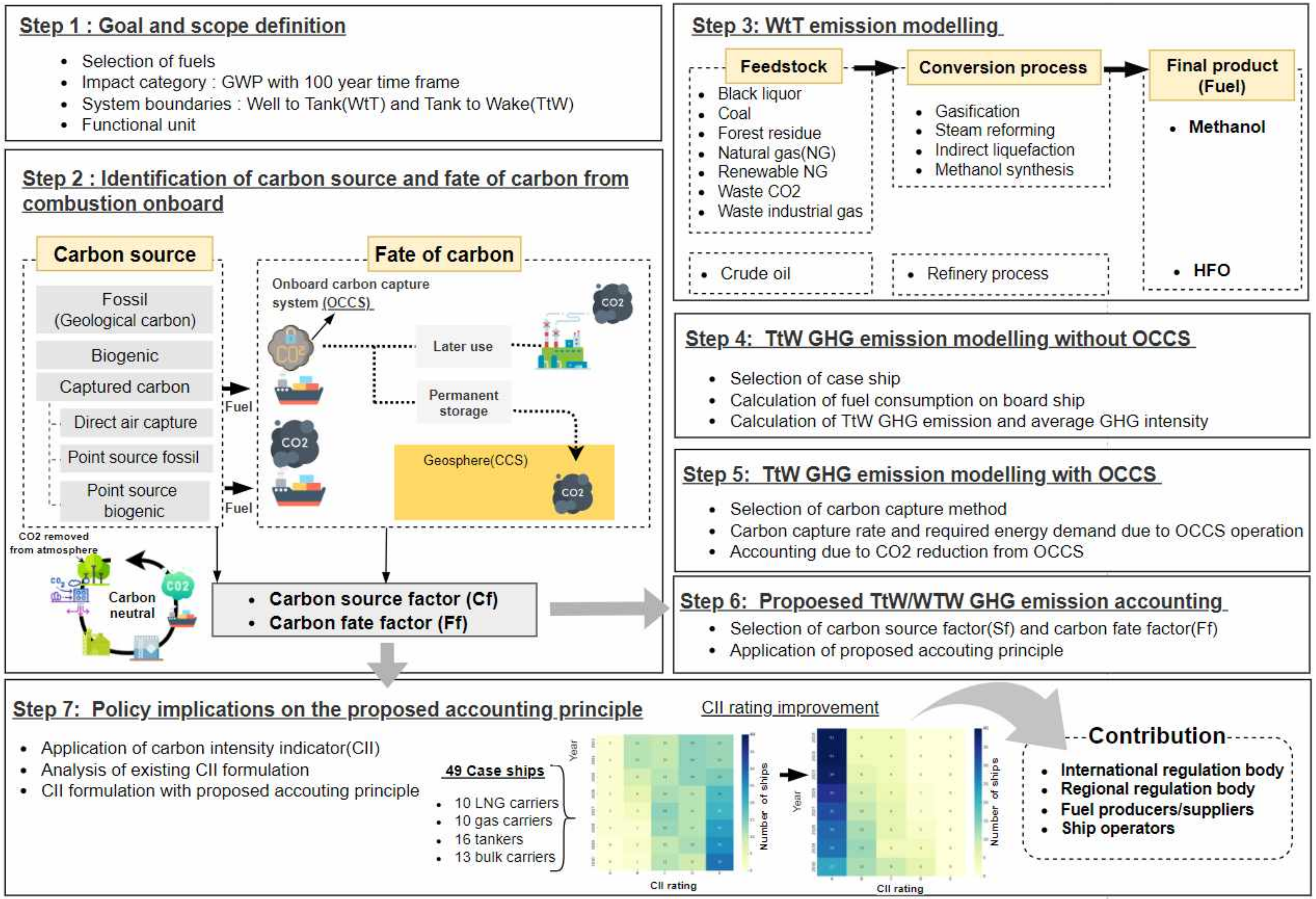


Figure 8-1 Proposed framework for accounting of GHG emissions and methodology flowchart

8.2.1 Goal and scope of the study

- Goal: The goal of this case study is to evaluate and calculate TtW emission through new framework on accounting of GHG emission in line with the IPCC Guidelines for National Greenhouse Gas Inventories from a life cycle perspective. It enables accounting of GHG emissions while avoiding double counting across sectors. Furthermore, the environmental benefits of utilizing the sustainable renewable fuel and OCCS during its operation are also considered.

- Scope: The system boundary of this study encompasses the entire life cycle of methanol fuel, from production and conversion to transport and distribution to end use. Additionally, it encompasses the fate of captured CO_2 (whether permanently stored or not), and adopts an attributional approach to evaluate their GHG impacts.

Table 8-1 Summary of the methodological choices

Methodological item	**Selection**
Selected fuels	HFO 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)

8.2.2 Identification of carbon source and fate of carbon from combustion onboard

When evaluating the life cycle carbon neutrality and sustainability of a fuel, it is crucial to determine not only the origin of the carbon contained in the fuel but also the fate of the carbon from combustion onboard ships. In this study, the term "carbon source" refers to the carbon origin of the feedstock used to produce marine fuels. This can include various sources such as fossil (geological carbon), biogenic carbon, captured carbon from direct air capture (DAC), captured carbon from point source fossil (PSF), captured carbon from point source biogenic (PSB), and mixed sources.

With regard to the fate of CO_2 from combustion onboard, CO_2 emissions from combustion onboard ships occur immediately. However, for ships equipped with onboard carbon capture and storage systems,(OCCS), it is possible to achieve no CO_2 emissions in the long term using methods such as CCS (which can lead to permanent storage), solid carbon capture, and infinite carbon capture and fuel use cycles.

Figure 8-2 explains zero and negative emissions in international shipping, with a specific focus on the carbon source and fate of CO_2 emissions from combustion.

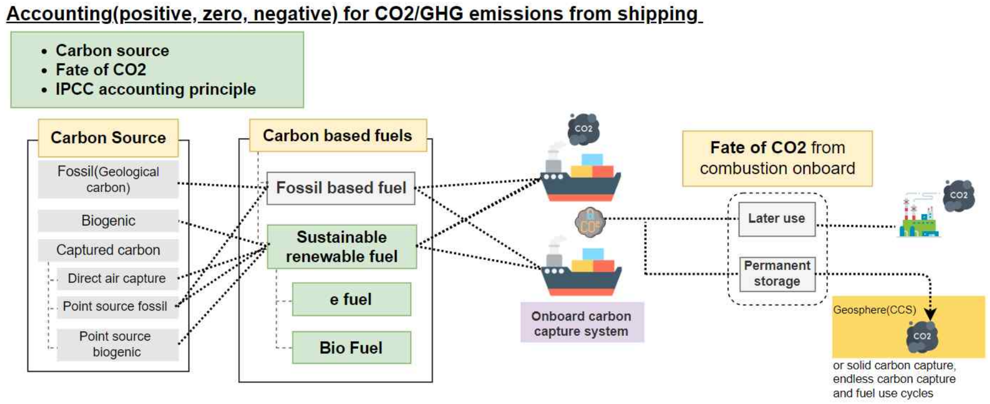


Figure 8-2 Conceptual diagram for proposed accounting of GHG emissions from shipping sector

(a) Carbon source factor

The carbon source factor (Sf) is designed to determine the TtW CO_2 emissions by assigning a value of either 1 or 0, based on the carbon source defined in the previous section. This factor serves dual purposes: firstly, for biofuels, it reflects the conceptual emissions credits accrued during biomass growth in the TtW analysis; secondly, for synthetic fuels derived from captured CO_2, it represents the emissions credits attributed to the utilization of captured CO_2 as a feedstock in the fuel production process within the TtW framework. The incorporation of Sf into the TtW emissions formula is crucial for the precise accounting of carbon emissions in international shipping, thereby encouraging the adoption of carbon-neutral fuels in the sector. Comprehensive details regarding the carbon source and the specific application of Sf in this study are delineated in Section 8.2.4 and 8.2.7. For this study, following carbon sources are defined to determine the carbon source factor, as indicated in Table 8-2.

i. Fossil (Geological carbon)

Geological carbon from fossil fuels has been sequestered for millions of years. Therefore, CO_2 emissions resulting from the combustion of fossil fuels should be accounted for as positive (+) emissions because the carbon they release is not a part of the current natural carbon cycle.

ii. Biogenic carbon

Biogenic carbon denotes the CO_2 that is sequestered from the atmosphere during the growth of feedstocks and subsequently released into the atmosphere when biofuels are combusted (Khan and Rehman, 2023). As a part of the natural carbon cycle, the process of photosynthesis employed by living plants consumes CO_2 from the atmosphere for plant growth, providing an opportunity to capture and sequester carbon during the conversion process to fuel and eventual combustion.

iii. Captured carbon : Direct Air Capture (DAC)

Direct air capture (DAC) of CO_2 refers to the extraction of CO_2 from ambient air, where the concentration of CO_2 is relatively low (Qiao et al., 2022). Although DAC has the potential to capture CO_2 on a larger scale and from any location, it is a relatively underdeveloped and potentially less effective technology due to the much lower concentration of CO_2 in the air compared to flue gases, resulting in a high energy requirement compared to other carbon capture techniques that utilize higher concentration sources of CO_2. If the process of capturing CO_2 is powered solely by renewable energy sources, it has the potential to deliver sustainable CO_2 that will not increase atmospheric levels.

iv. Captured carbon: Point source fossil (PSF)

Point source fossil (PSF) carbon capture refers to CO_2 released during the combustion of fossil fuels for power or heat generation, as well as from industrial processes like chemical production, mineral production, natural gas processing, and iron and steel production. In these cases, CO_2 is not directly emitted through fossil fuel combustion but can be generated through chemical processes using non-fossil fuel substrates, leading to CO_2 release (Hansson et al., 2017).

Contrary to synthetic fuels (e-fuels) obtained through Direct Air Capture (DAC) and Point Source Biogenic (PSB), synthetic fuels produced from PSF sources should not be considered carbon-neutral but rather as delayed CO_2 emissions (Mukherjee et al., 2023). This is because the CO_2 derived from fossil fuels will eventually be re-emitted into the atmosphere during the combustion process, making its use potentially unsustainable. However, it's important to note in this study, industrial process gases or emissions (e.g., from non-combustion chemical reactions or flare gas) are considered differently. They are viewed as an unavoidable and unintentional consequence of the production process in industrial installations, thus warranting a separate consideration under the accounting principles, as also detailed in Section 8.2.6.

v. Captured carbon : Point source biogenic (PSB)

This CO_2 from point source refers to CO_2 produced by combustion of biofuels or by-product CO_2 produced in the process of biofuel production.

As Table 8-2 illustrates, this study focuses on carbon-based fuels to advocate for a carbon-neutral approach in the shipping industry. The system boundary includes the entire fuel life cycle, encompassing production, conversion, transportation, distribution, and end-use. Additionally, this study examines the fate of captured CO_2 onboard within the system boundary.

(b) Carbon fate factor

In this study, the carbon fate factor (Ff) is designed to determine whether captured carbon onboard can count toward TtW emissions reduction credits. The IPCC guidelines (Eggleston et al., 2006) on carbon capture and utilization (CCU) state: 'Quantities of CO_2 intended for later use or short-term storage should not be deducted from reported CO_2 emissions unless these emissions are accounted for elsewhere in the inventory.' Applying this principle to captured CO_2 from international shipping leads to the interpretation that “Quantities of CO_2 for later use and short-term storage should not be deducted from CO_2 emissions except when the CO_2 emissions are accounted for elsewhere in the inventory." In line with this context, Ff is assigned a value of 1 for permanently stored captured CO_2, and a value of 0 for captured CO_2 intended for other uses. The details of its functionality are indicated in formulas 8-11 and 8-12.

Table 8-2 Categories for determining zero and negative emissions

Carbon Source		Carbon Source factor	Fate of CO_2 from combustion onboard	
			CO_2 emission[a]	No CO_2 emission in the long term[b]
Fossil		0	Positive emission	Zero emission
Biogenic[c]		1	Zero emission (carbon neutral)	Negative emission
Captured carbon	Point source fossil	1 or 0	Delayed emission[d]	Zero emission
	Direct air capture	1	Zero emission (carbon neutral)	Negative emission
	Point source biogenic	1	Zero emission (carbon neutral)	Negative emission

[a] CO2 emissions can occur either immediately or as a result of intermediate carbon capture and utilization(CCU)

[b] By utilizing methods such as CCS (possibly leading to permanent storage), solid carbon capture, and endless carbon capture and fuel use cycles, it is possible to achieve no CO2 emissions in the long term

[c] It is assumed that the sustainability criteria have been achieved.

[d] Captured carbon from fossil point source used for fuel production can be regarded as delayed emission(such as carbon recycling) since it will eventually be emitted.

8.2.3 WtT GHG emission modelling

(a) Selected fuel pathway and GHG emissions

This study primarily focuses on methanol, examining its production pathway as depicted in Figure 8-3. Methanol production involves various pathways, each characterized by specific feedstocks and conversion technologies This study focuses on methanol and identifies its production pathway, as outlined in Figure 8-3. Methanol can be produced through various distinct pathways, determined by the feedstock and conversion technology. As shown in Table 8-3, the carbon sources are also determined based on their defined categories in the previous section. The WtT GHG emissions for each production pathway can be calculated by considering feedstock production or collection, transportation of feedstocks, intermediates, and final products, and conversion of feedstocks into final fuels. The life cycle analysis for this study was conducted using the methanol fuel pathways derived from black liquor, coal, biomass(forest reside) natural gas, renewable natural gas, waste CO_2 and waste industrial gas (flare gas) in the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model developed by Argonne National Laboratory (ANL) (Wang et al., 2021). Detailed descriptions of these pathways, based on the feedstocks used, are provided below.

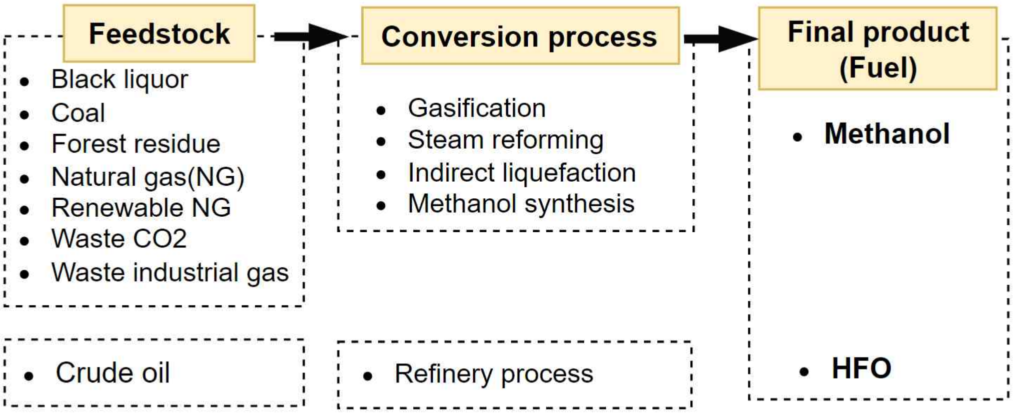


Figure 8-3 Selected fuel production pathway

Table 8-3 Description of carbon sources depending on feedstock

No.	**Feedstock type**	**Carbon source**	**Description on carbon source**
1	Black liquor	Biogenic carbon	Black liquor is typically derived from wood pulping processes, which involves biogenic carbon (from trees) (Kuparinen et al., 2019).
2	Coal	Fossil	The use of coal as a feedstock for methanol production involves geological carbon, which is fossil in origin
3	Forest residue	Biogenic carbon	Forest residue is a biogenic source, as it comes from trees and plant matter (Bukhtiyarova et al., 2017).
4	Natural gas	Fossil	Natural gas is typically of geological fossil origin (Sarp et al., 2021).
5	Renewable natural gas	Biogenic carbon	Renewable natural gas is produced from organic materials, such as agricultural waste or landfill gas, which are biogenic carbon sources (Kang et al., 2021).
6	waste CO2 with	Captured carbon_Fossil	Waste CO_2 is captured from industrial processes, including chemical reactions, which is consistent with the captured

	renewable electricity		carbon from point source fossil (PSF) category (Meunier et al., 2020).
7	Waste industrial gas	Captured carbon_Fossil	This pathway utilizes waste industrial gas, specifically flare gas, as a source for methanol production. This aligns with captured carbon from point source fossil (PSF) (Corbett and Winebrake, 2018).

i. Methanol from black liquor

Methanol is produced from waste wood through the utilization of black liquor, a by-product generated in the wood-to-pulp process at mills for paper production. The syngas produced through the gasification of black liquor is employed for methanol production (Domingos et al., 2022).

ii. Methanol from coal

The conventional methanol production process utilizing coal as its raw material can be delineated into four distinct stages: syngas generation through coal gasification, syngas reforming, methanol synthesis, and the final purification via methanol distillation (Bozzano and Manenti, 2016, Liu et al., 2020b).

iii. Methanol from forest residue

Forest residues are employed as the feedstock for the production of methanol derived from biomass. Prior to the gasification step, these forest residues undergo drying and preheating processes. The syngas generated during the gasification process is utilized in the production of methanol (Brynolf et al., 2014).

iv. Methanol from natural gas

Methanol production predominantly utilizes a gas-to-methanol process with natural gas as the primary carbon source (Zhang et al., 2017). Typically, a gas-to-methanol process comprises three main units: a syngas production unit, a methanol production unit, and a methanol upgrading unit (Gao et al., 2020).

v. Methanol from renewable natural gas

This pathway utilizes landfill gas as the feedstock for methanol production. In this study, we assume that the methanol production facility is situated at the same location as the landfill gas source, eliminating the need for transportation to the production facility (Corbett and Winebrake, 2018).

vi. Methanol from waste CO_2 and renewable electricity

Methanol is produced using carbon dioxide captured from flue gas or other waste streams, in combination with hydrogen produced via electrolysis using renewable energy, which holds significant potential for achieving very low, or even negative, GHG emission (Ellis and Svanberg, 2018).

vii. Methanol from waste industrial gas

While this pathway is similar to the production of methanol from natural gas, the natural gas utilized here is sourced from flare gas, a type of waste industrial gas. In this study, we assume that shifting flared gas to methanol production generates emissions credits. This assumption is based on the understanding that if this flared gas were not used for methanol production, it would have resulted in the release of carbon dioxide through combustion (Yelvington et al., 2023).

8.2.4 TtW GHG emission modelling without OCCS

(a) Selection of case ship

To compare WtW and TtW emissions between methanol and HFO, a very large crude carrier (VLCC) was selected as the case ship. The main particulars of the selected ship, as shown in Table 8-4, were obtained from the Korean Register.

Table 8-4 Specifications of the case ship

Specification	Details
Length × Breadth × Depth	327 m × 60 m× 27.87 m
Service speed	14.8 knots
Deadweight	50,655 tons
Main Engine	Low-speed diesel cycle engines (LSD) (7G80ME-LGIM)
MCR/NCR	MCR: 24,500 kW × 66.1 RPM NCR: 17,689 kW × 59.3 RPM

Methanol is employed as a marine fuel on the Stena Germanica car ferry in Sweden, utilizing Wartsila's methanol DF retrofit concept, as well as on over ten ocean-going tankers equipped with MAN's newly developed methanol DF engines, known as ME-LGI (Dierickx et al., 2019) Both MAN's methanol DF concept for 2-stroke SSD engines and Wartsila's concept for 4-stroke MSD engines are applicable for retrofitting existing engines and for new-build installations (Aakko-Saksa et al., 2023). For the purposes of this study, the ME-LGI engine has been selected, as it is specifically designed to accommodate the high-pressure injection of liquid fuels (Oloruntobi et al., 2023). It's important to highlight that two-stroke dual-fuel engines powered by methanol require the presence of a pilot fuel, which can be either diesel or gasoil, for combustion. The pilot fuel constitutes between 5% and 10% of the overall fuel mixture, with the precise proportion varying depending on the engine type and operating load.

Table 8-6 displays specific fuel consumption and emission factors specific to the auxiliary engine, with these emission factors derived from the 4th IMO GHG study. For the purposes of our analysis, we have assumed an auxiliary engine power output of 860 kW during sea operations, taking into account factors such as ship type, size, and operational mode for the selected case ship (IMO, 2020).

(b) Calculation of fuel consumption on board ship

The scope of fuel consumption considered in this study encompasses not only that of main engines but also auxiliary engines, which are responsible for the majority of emissions produced by ships (IMO, 2020). Notably, the fuel consumption of the auxiliary boiler is not included in this calculation, since it does not operate during seagoing operations. Regarding the dual-fuel engine, it has the capability to operate in either diesel or alternative fuel mode. When in diesel mode, the engine functions as a typical internal combustion engine that runs on diesel (Bui et al., 2022). Therefore, the subsequent equations are used to determine the total annual fuel consumption in these cases.

- $FC_{primary} = \sum_{i=1}^{n} AML_i \times SFOC_i \times AD_i$ (8-1)
- $FC_{pilot} = \sum_{i=1}^{n} AML_i \times SPOC_i \times AD_i$ (8-2)

- $\mathrm{FC_{aux}} = \sum_{i=1}^{n} \mathrm{AML_i} \times \mathrm{SFOC_i} \times \mathrm{AD_i}$ (8-3)

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

Table 8-5 The operational profiles and emission factor for estimating annual TtW GHG emissions for main engines using HFO and methanol

	HFO fueled engine	Methanol engine
Engine Maker's Model	7G80ME	7G80ME-LGIM
Average main engine load at sea and operation days	55% of MCR /250 days	
Engine thermal efficiency (%) at 55 % of MCR	55	54
SFC (g/kWh) at 55 % of MCR (Main /pilot fuel)	166.98 / -	294.3/15.0
Emission factor (GHG t/t fuel) (IMO, 2018a, Pavlenko et al., 2020, IMO, 2020)		
CO_2	3.144	1.375
CH_4	0.00006	0.000006
N_2O	0.00016	0.000016

Table 8-6 The emission factors for estimating annual TtW GHG emissions from auxiliary engine

Fuel	HFO	Methanol
Engine type	Medium-speed diesel cycle engines (MSD)	
SFOC (g/kWh)	195	370
Emission factors (GHG t/t fuel) (IMO, 2020)		
CO_2	3.144	1.375
CH_4	0.00006	0.000006
N_2O	0.00025	0.000025

(c) Calculation of TtW GHG emissions and average GHG intensity

Once all fuel consumptions associated with main and auxiliary engines are estimated and computed, TtW GHG emissions can be calculated, as expressed in the following equation :

- $\mathrm{E_{base}} = \sum_{i}^{n\ \mathrm{fuel}} \sum_{j}^{m\ \mathrm{engine}} \mathrm{M_{i,j}} \times \mathrm{EF_{GHG}}$ (8-4)

- $EF_{GHG} = C_{fCO2} + C_{fCH4} \text{ x } GWP_{CH4} + C_{fN2O} \text{ x } GWP_{N2O}$ (8-5)

The average GHG intensity(GHG_I) of the fuel used on board ships are estimated using the following equation:

- $GHG_I = \frac{E_{base}}{\sum_i^n M_i \times LHV_i}$ (8-6)

where; E_{base}: 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), 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, and LHV : Lower heating value of $fuel_i$

8.2.5 Consideration of OCCS in TtW GHG emission modelling

When contemplating the application and installation of OCCS technology on board ships, it is crucial to take into account both the vessel size and voyage range, as these factors significantly influence the feasibility and effectiveness of CCS deployment and CO_2 storage capacity. This is mainly due to the space limitations for CO_2 storage tanks and CCS equipment, as well as the energy demands of the CCS operation, which may necessitate additional fuel (Law et al., 2023).

(a) Selection of carbon capture method

There are three primary types of CO_2 capture systems: post-combustion, pre-combustion, and oxyfuel combustion (Theo et al., 2016). Pre-combustion and oxyfuel combustion processes extract carbon from the fuel before combustion, resulting in the production of hydrogen and oxygen for subsequent combustion. As a result, the pre-combustion and oxyfuel combustion carbon capture systems necessitates integration into the fuel supply and power generation systems, requiring a comprehensive redesign (Wilberforce et al., 2019, Olabi et al., 2022). The selected carbon capture system in this study is an amine solvent-based technology, which is the most commonly studied type of CCS, particularly the post-combustion solvent-based CCS, especially monoethanolamine (MEA) (Borhani and Wang, 2019, Wang et al., 2011, Bahman et al., 2023). This system comprises an absorber, where the solvent absorbs CO_2, and a stripper, where CO_2 separation is facilitated by thermal energy from a reboiler (Ros et al., 2022).

The potential capture rate, achievable if all exhaust heat is utilized for solvent regeneration, is determined. Thus, the potential CO_2 capture rate of a ship as a function of the exhaust temperature based on the available heat in the exhaust gas, calculated by following equation (Ros et al., 2022):

- $\text{Capture rate} = \frac{Q_{avail}}{Q_{reboiler}} = \frac{Cp_{exh.gas} \times m_{exh.gas} \times \Delta T_{exh.gas}}{m_{co2} \times SRD \times 10^3}$ (8-7)

Where, Q_{avail} : the available heat in exhaust gas (kJ/kg_{CO2}), $Q_{reboiler}$: specific heat duty or energy required by the reboiler for CO2 separation ($kJ/ kg_{CO2\ captured}$), $Cp_{exh.gas}$: the specific heat of the exhaust gas (kJ/kg.K), $m_{exh.gas\ or\ CO2}$: the mass flow rate of the exhaust gas or CO2, ΔT : Temperature difference(°C) between the available waste heat temperature and the reboiler temperature, and SRD : the specific reboiler duty of the selected carbon capture system(MJ/kg_{CO2})

From a practical perspective, engine exhaust gas heat capacity remains stable irrespective of its composition (Voice and Hamad, 2022). In this calculation, the flow of exhaust gas is estimated at 30 kg/s, collected from the engine manufacturer's engine selection software (MAN CEAS Engine Calculations), with the estimation of the CO_2 mass fraction in the exhaust gas at approximately 4.3%. The average specific heat of the exhaust gas is reported as 1.08 kJ/kg-K (Ros et al., 2022, Lee et al., 2021). Excess steam from the main engine exhaust gas economizers, which recover waste heat, can be utilized to reduce the additional heat energy required. Based on operational data from a Korean shipping company, the available waste heat temperature is approximately 185°C, originating from the outlet of exhaust gas economizers. The assumption is that this heat can be extracted, lowering the exhaust gas temperature from 185°C to 135°C. This approach maintains a safety margin of 15°C, ensuring that the reboiler operates at 120°C, with energy transferred through a heat transfer fluid (Voice and Hamad, 2022, Ros et al., 2022). We assume a reboiler heat duty of 3.2 MJ/kgCO2, which falls within the range of literature values between 2.88 MJ/kg CO_2 and 3.6 MJ/kg CO_2, all of which are based on the use of MEA as the capture solve(Feenstra et al., 2019, Gorset et al., 2014, Stec et al., 2016, Thaler et al., 2022, Feron et al., 2020). For the calculation of the potential CO_2 capture rate, Table 8-7 summarizes the relevant parameters and their corresponding values.

Table 8-7 Key parameters for the calculation of the potential CO_2 capture rate

	Parameters for potential capture rate calculation	Numerical Values
1	Average specific heat of the exhaust gas (KJ/kg.K)	1.1
2	Available heat temperature in the exhaust gas (°C)	180.0
3	Reboiler operating temperature (°C)	135.0
4	Exhaust gas flow (kg/s)	33.2
5	CO2 mass fraction in the exhaust gas	0.043
6	CO2 flow (kg/s)	1.4
7	Specific reboiler duty (MJ/kg CO2)	3.2
8	Available heat in exhaust gas (kJ/s)	1613.5
9	Specific heat duty or energy required by the reboiler for CO2 separation (kJ/s)	4568.3

While a maximum capture rate of 90% is assumed, in line with the majority of studies (Feenstra et al., 2019), the baseline capture rate in this study was determined based on the condition that includes the available heat in exhaust gas, as shown in Table 8-7. Three scenarios of capture rates were considered: baseline, 50%, and 90%. Additionally, the study assumes that only CO_2 is captured among the GHGs in the exhaust when calculating the capture rate.

(b) Carbon capture rate and required energy demand due to OCCS

All carbon capture systems require energy, and increasing the recovery rate of waste heat from the engines' exhaust gas can reduce the need for additional energy sources (Feenstra et al., 2019). However, this increased energy demand creates a feedback loop where enhancing the capture rate may lead to higher fuel consumption and emissions, which then need to be captured. It is important to note that the auxiliary boiler is not typically operated during the ship's normal seagoing operation. In this study, however, additional auxiliary boiler load was calculated to provide the necessary heat energy for the specific reboiler duty. CO_2 is stored on board in a liquefied state. For this process, it is assumed that CO_2 is compressed prior to liquefaction to about 15 bar, with an electricity consumption of 0.05 kWh/kg_{CO2} (Feenstra et al., 2019). The electric energy demand for CO_2 liquefaction is estimated at 0.03 kWh/kg_{CO2}, and for auxiliaries, it stands at 0.027 kWh/kg_{CO2} (Emrrah.durusut 2018, Thaler, Kanchiralla et al. 2022). This study accounts for the additional emissions resulting from the operation of OCCS using the following equation:

- $\mathrm{E_{OCCS}} = \mathrm{E_{base}} + \mathrm{E_{penalty}}$ (8-8)
- $\mathrm{E_{penalty}} = \mathrm{FC_{OCCS}} \times \mathrm{EF_{GHG}}$ (8-9)
- $\mathrm{FC_{OCCS}} = \sum_{i}^{n} \sum_{k}^{m} (\mathrm{OCCS_{E_{i,k}}} \times \mathrm{SFOC_{i,k}} \times 10^{-6})$ (8-10)

where; E_{OCCS} : Total annual CO_2 emissions, including those from the operation of OCCS, $E_{penalty}$: Additional emissions generated due to the energy penalty necessary to power OCCS equipment, FC_{OCCS} : Additional annual fuel consumption(ton) necessary for operating the auxiliary engine (i) and boiler (k) during OCCS operation. The consumption is calculated using $OCCS_{E\ i,k}$ (kWh), which represents the annual required energy, and $SFOC_{i,k}$ (g/kWh), which represents the specific fuel consumption, EF_{GHG} : TtW GHG emission factors, representing the average GHG intensity of the fuel used (CO_2 eq./MJ)

The net decrease in emissions can be evaluated by deducting the additional emissions required for system operation from the total amount captured and comparing this difference to the original level of emissions produced during normal operation with reference fuel.

(c) *Accounting due to CO2 reduction from OCCS*

As outlined in Section 8.2.2, the following equation , incorporating the carbon fate factor (Ff), is presented to appropriately address the accounting issues discussed in this study.

- $E_{occs} = F_f \times e_{occs}$ (8-11)

where; e_{occs} : CO_2 reduction credit from carbon capture and storage onboard, (Ff) : carbon fate factor, which determines if captured carbon onboard can be counted toward TtW emissions reduction credits. The carbon fate factor takes values of either 0 or 1.

8.2.6 Proposed TtW GHG emission accounting

Considering the carbon source factor and carbon fate factor, the following equation is employed for effective TtW GHG emission accounting:

- $Ea = \sum_{i}^{n\ fuel} \sum_{j}^{m\ engines\ ,\ boilers} M_{i,j} \times EF_{GHG} - S_f \times e_c - F_f \times e_{occs}$ (8-12)

where; e_c : emission credits derived from the utilization of captured CO_2 as a carbon stock in the production process of synthetic fuels or the emission credits generated by biomass growth. For the purposes of this study, the CO_2 emissions from engines and boilers using fuels with a carbon source factor (Sf) of 1 were treated as emission credits, equivalent to those defined by e_c.

The following principles are applied through the proposed TtW GHG emission accounting in this study:

- For methanol derived from fossil sources like natural gas or coal, the CO_2 emissions from the combustion in internal combustion engines and boilers are accounted for as net positive emissions. These emissions often represent the largest share of emissions over the entire life cycle of the fuel.
- Fuels based on renewable carbon sources, such as biomass, biogas, or the organic fraction of waste, are treated as climate-neutral in their TtW emissions. The rationale is that the carbon for these fuels was previously absorbed from the atmosphere during plant growth. The same principle applies to carbon sourced from DAC, which is also considered climate-neutral.

- Emissions resulting from the combustion of fuels produced using carbon derived from gases or exhaust gases, which are unavoidable by-products of industrial processes, are excluded from TtW emission calculations. This exclusion applies even if the by-products originate from fossil sources. An example of this is methanol synthesized using captured carbon from fossil point sources (PSF), like waste CO_2 (with renewable electricity) or waste industrial gas. In these cases, the emissions from ships using this methanol are not included in TtW emissions. This is because such emissions are deemed an unavoidable outcome of the industrial process, and their utilization in fuel production does not alter their initial impact on the atmosphere.

To simplify the analyzed scenarios in Section 8.2.2 to Section 8.2.5, the feedstocks used for methanol production — including black liquor, forest residue, renewable natural gas (RNG), waste CO_2, and waste industrial gas as enumerated in Table 8-3— are classified as 'Renewable' for the purpose of calculating TtW GHG emissions within the proposed framework (refer to Table 8-8). Consequently, these feedstocks are assigned a substitution factor (Sf) of 1. In contrast, feedstocks such as coal, natural gas, and crude oil are designated as 'Fossil,' and are accordingly assigned an Sf of zero. Additionally, the carbon fate factor (Ff) is determined based on the permanence storage since OCCS, with a value of 1 for permanent storage and 0 otherwise.

Table 8-8 The selection of carbon source factor (Sf) and carbon fate factor (Ff)

Fuel Type	Scenarios No.	Whole pathway depending on carbon source and carbon fate	Sf	Ff
Methanol	SN.1	Fossil + OCCS + no permanent storage	0	0
	SN.2	Renewable + OCCS +no permanent storage	1	0
	SN.3	Fossil + OCCS + permanent storage	0	1
	SN.4	Renewable + OCCS + permanent storage	1	1
HFO	SN.5	Fossil + OCCS + no permanent storage	0	0
	SN.6	Fossil + OCCS + permanent storage	0	1

8.2.7 Policy implications on the proposed accounting framework

To evaluate the impact of the proposed accounting principle on existing energy efficiency framework of international shipping sector, we collected operational data for a total of 49 ships from a Korean shipping company known for operating a diverse fleet. The dataset included 10 LNG carriers, 10 gas carriers, 16 tankers, and 13 bulk carriers, covering metrics such as deadweight tonnage (DWT), average operating speed, annual fuel consumption, and annual total distance travelled in miles. Initially, the Carbon Intensity Indicator (CII) for these ships was calculated within the existing ship energy efficiency framework. Subsequently, the CII using the proposed accounting equation was evaluated and compared to the current framework. These aspects are covered in greater detail in the sections below.

(a) Application of carbon intensity indicator(CII) for international shipping

The CII assesses a ship's efficiency in transporting either goods or passengers by calculating the amount of CO_2 emitted relative to the vessel's size/capacity and the distance travelled (IMO, 2021c). This section presents the current definition of the CII, which covers both the attained and required values, as well as ship categorization. Additionally, the application of the CII through proposed TtW emission accounting is introduced.

i. Existing CII formulation

The CII is an annual indicator based on the efficiency of ships during services. The attained CII is calculated by using the following equation, which involves dividing the total amount of CO_2 emitted by a ship during a calendar year by the total amount of transport work it performed during that period (IMO, 2021e):

- $\text{Attained CII} = \frac{FC_j \times C_{Fj}}{\sum C \times D_t}$ (8-13)

where; FC_j is the yearly consumption (mass) of the j-type fuel oil; C_{Fj} is the emission factor for the j-type fuel oil, C is the gross tonnage GT, and Dt is the total nautical miles travelled during the calendar year.

Within the equation, the value GT is a constant, whereas the other variables are contingent upon the ship's operations. As with all of the IMO indices, the annual attained CII is subject to a reference value that serves as the basis for assessing compliance with the requirements. This reference value is determined by applying the following equation (IMO, 2021e)

- Required annual operational CII $= \left(1-\frac{z}{100}\right) \times \mathrm{CII}_{\mathrm{Ref}}$ (8-14)

where; $\mathrm{CII}_{\mathrm{Ref}}$ is specific reference value of year 2019 depending on ship type lines with following formular (IMO, 2021d) , $\mathrm{CII}_{\mathrm{Ref}} = a \times \mathrm{Capacity}^{-c}$: Capacity is measured in deadweight tons or gross tons, depending on the type of ship, “a and c are parameters estimated through median regression fits, taking the attained CII and the Capacity of individual ships collected through IMO DCS in the year 2019, Z is the reduction factors for the required annual operational CII of various types of ships from 2023 to 2030, as shown in Table 8-9. The Z factors for the years 2027 to 2030 have not been determined yet, but in this study a gradual increase of 2.75% was applied based on the supply-based CII reduction target of 22% (IMO, 2021b)

Table 8-9 Reduction factor (Z%) for the CII relative to the 2019 reference line

	2023	2024	2025	2026	2027	2028	2029	2030
Reduction factor	5%	7%	9%	11%	Review to be conducted by January 2026, but expected to be in the range from 11% to 22%			

Figure 8-4 Parameters for reference CII calculation and CII rating boundaries depending on ship type

Ship Type	DWT	a	c	Capacity	dd vectors			
					d1	d2	d3	d4
LNG Carrier	≥ 100,000	9.827	0	DWT	0.89	0.98	1.06	1.13
	≥ 65,000	1.45E+14	2.673	DWT	0.78	0.92	1.1	1.37
	< 65,000	1.45E+14	2.673	65000				
Gas carrier	≥ 65,000	1.44E+11	2.071	DWT	0.81	0.91	1.12	1.44
	< 65,000	8104	0.639	DWT	0.85	0.95	1.06	1.25
Tanker		5,247	0.61	DWT	0.82	0.93	1.08	1.28
Bulk	≥ 279,000	4,745	0.622	279,000	0.86	0.94	1.06	1.18
	< 279,000	4,745	0.622	DWT				

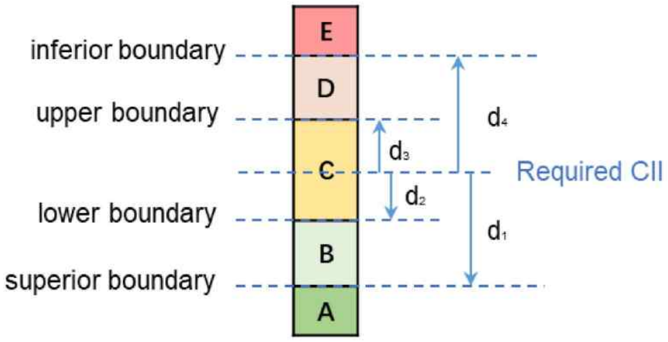


Figure 8-5 Vectors and CII rating bands (IMO, 2021f)

As depicted in Table 8-6, the criteria for assigning CII ratings are based on the required annual operational CII for each vessel, assessed in conjunction with the deviation values. These deviations, represented as 'dd vectors', quantify the direction and extent of each vessel's deviation from the mandated CII value. The establishment of rating boundaries reflects the distribution of CIIs across individual ships. In line with IMO guidelines (IMO, 2021f), the central 30% of the fleet segment, gauged by their achieved annual operational CII, is allocated a 'C' rating. The highest 35% of ships, further categorized into the upper 20% and the subsequent 15%, are expected to be assigned 'D' and 'E' ratings, respectively. In contrast, the lowest 35% of ships, divided into 20% and 15%, are projected to receive 'B' and 'A' ratings, correspondingly. The assignment of these ratings, along with their respective dd vectors, is detailed in Figure 8-5.

ii. Proposed revision of the CII formulation

Given that the CII reflects a ship's efficiency, and considering the challenges in controlling or determining whether captured CO_2 from ships is permanently stored onshore or offshore, this study treats captured CO_2 as a reduction in the CII calculation. This approach implies that the value of the carbon fate factor (Ff) is consistently set at 1. It is important to note that the current CII regulation focuses solely on CO_2; therefore, this section also confines its scope to CO_2 for an effective comparison. To ensure accurate accounting of TtW CO_2 emissions with the use of sustainable renewable fuels and OCCS in the current CII framework, the following equation is proposed, reflecting Section 8.2.5.

- Proposed Attained CII $= \frac{\mathrm{FC_j} \times C_{Fj} - S_F \times e_c - \mathrm{F_f} \times \mathrm{e_{occs}}}{\sum \mathrm{C} \times \mathrm{D_t}}$ (8-15)

As discussed in Section 3.6, it's important to note that the variable 'ec' is equivalent to the quantity of CO_2 emissions(C_F) emitted from the ship. The installation of OCCS results in additional space requirements and cargo loss, leading to a reduction in deadweight. Drawing from existing literature (Lee et al., 2021, MMMCZCS, 2022), a 3.5% reduction has been applied in this study to account for the decrease in deadweight tonnage, a critical factor in assessing the impact of OCCS installation on ship operational efficiency. Among the three carbon capture rate scenarios presented in Section 8.2.5, the baseline scenario, which utilizes available exhaust gas heat, was selected for the CII comparison. In this scenario, the additional CO_2 emissions resulting from the energy demands of the OCCS have been estimated.

8.3 Analysis results

8.3.1 Comparison of WtT GHG emissions from fuels

Figure 8-6 presents the WtT GHG emissions associated with selected methanol production pathways, with a focus on varying feedstocks. Pathways utilizing biogenic carbon — sourced from black liquor, forest residue, and renewable natural gas — demonstrate WtT emission factors significantly lower than those from fossil carbon sources, such as coal and natural gas. Notably, pathways that utilize captured carbon, particularly from fossil sources, show negative WtT emissions, indicating a net removal of CO_2 across the methanol production life cycle. The results display a wide spectrum of WtT emissions, ranging from as low as -66.26 CO_2 eq./MJ for methanol produced using captured CO_2 and renewable electricity, to as high as 89.12 CO_2 eq./MJ for methanol derived from coal. This considerable variance emphasizes the critical impact of carbon sourcing on the life cycle emissions of methanol production. The stark contrast in WtT GHG emissions between biogenic and fossil carbon sources underlines the urgency of transitioning towards renewable energy sources in methanol production, a move that is essential not only for environmental sustainability but also for meeting global climate change mitigation goals.

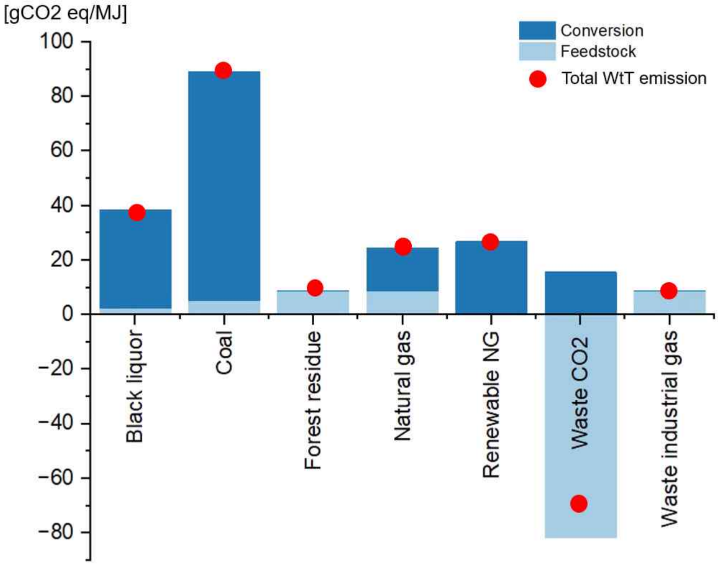


Figure 8-6 WtT GHG emissions depending on methanol production pathway

8.3.2 Comparison of TtW GHG emissions

Figure 8-7 illustrates the reduction in GHG emissions across three different carbon capture rate scenarios, regardless of the feedstock, carbon source, or the fate of the captured carbon. It demonstrates that the implementation of OCCS significantly impacts the annual GHG emissions from ships using methanol and HFO. In the baseline scenario without OCCS, methanol emissions are registered at 39,398 tons, while HFO emissions are at 46,271 tons. When OCCS is employed, emissions are reduced in all scenarios, with the effectiveness increasing proportionally to the carbon capture rate.

For the 50% carbon capture rate, methanol sees an additional emission due to the energy penalty of 4,132 tons (10.5% increase) and HFO sees 5,789 tons (12.5% increase). However, the net emissions after OCCS are reduced by 44.5% for methanol and 43.0% for HFO compared to the baseline.

At the 90% capture rate, the additional emissions for methanol are 18,574 tons (47.1% increase) and for HFO, 26,022 tons (56.2% increase). Despite this energy penalty, the total emissions after OCCS are significantly reduced, by 84.9% for methanol and 83.1% for HFO, indicating an overarching positive impact of OCCS on GHG emissions.

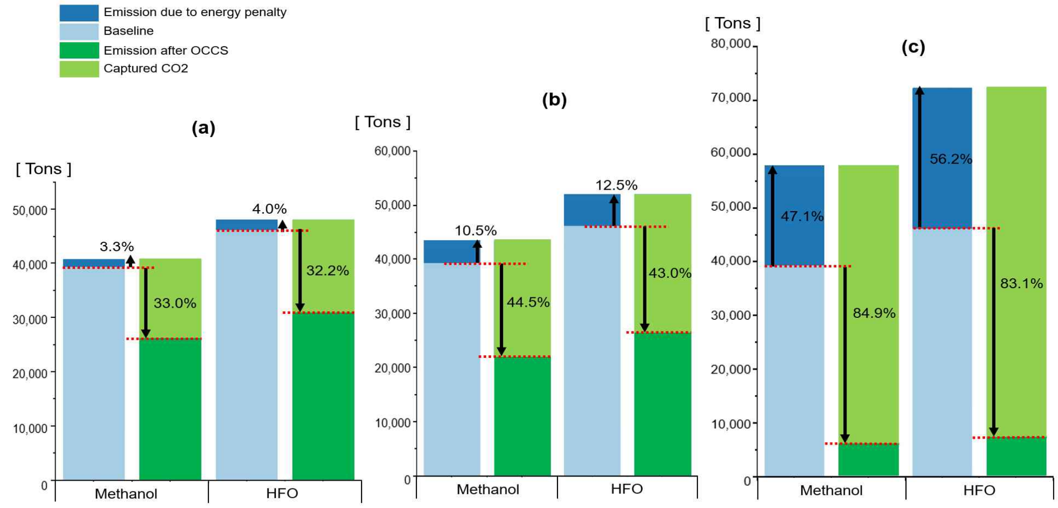


Figure 8-7 GHG emission reduction across three carbon capture rate scenarios: (a) Baseline with available exhaust gas heat, (b) 50%, and (c) 90%

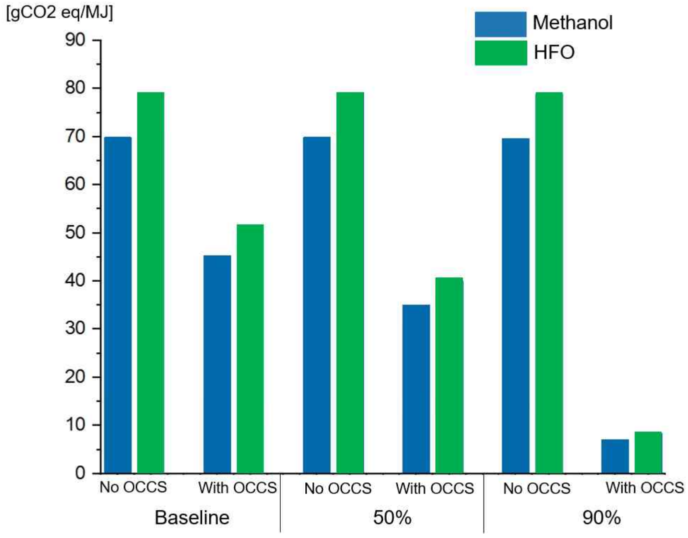


Figure 8-8 GHG intensity comparison for HFO and methanol with and no OCCS Implementation

As depicted in Figure 8-8, the TtW GHG intensity (CO_2 eq./MJ) reveals significant reductions in GHG emissions intensity as the carbon capture rate increases for both methanol and HFO. In the baseline scenario without carbon capture, methanol exhibits a GHG intensity of 69.9 CO_2 eq./MJ, while HFO shows 79.3 CO_2 eq./MJ. The implementation of OCCS reduces these intensities to 45.3 and 51.7 CO_2 eq./MJ, respectively, indicating a substantial decrease in emissions intensity due to OCCS application.

With a 50% carbon capture rate, the GHG intensity decreases further to 35.1 CO_2 eq./MJ for methanol and to 40.1 CO_2 eq./MJ for HFO. At the highest evaluated capture rate of 90%, the TtW GHG intensity shows a dramatic reduction, with methanol at 7.1 CO_2 eq./MJ and HFO at 8.5 CO_2 eq./MJ, representing a significant reduction in emissions intensity from the baseline.

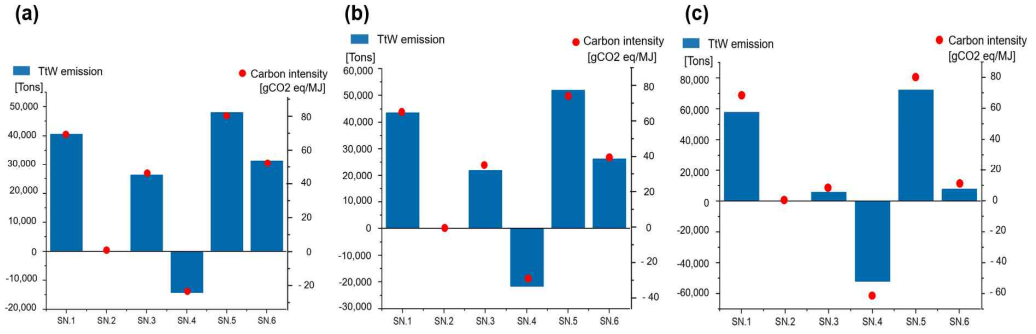


Figure 8-9 TtW GHG emissions and carbon intensity across various carbon capture rates : (a) base (35%), (b) 50%, and (c) 90%

Figure 8-9 presents an evaluation of TtW GHG emissions and carbon intensity for methanol and HFO under three carbon capture scenarios: base (35%), 50%, and 90%. At the base capture rate, methanol's emissions range from zero in the best-case scenario (SN.2) to negative (-14,321 tons) when combined with renewable sources, OCCS, and permanent storage (SN.4), demonstrating the potential for renewable energy to significantly reduce emissions. In contrast, HFO shows considerable emissions across all scenarios, with the lowest emissions corresponding to the use of permanent storage (SN.6), indicating the limitations of fossil fuels.

At a 50% capture rate, methanol reaches zero emissions for scenarios involving renewable sources without permanent storage (SN.2) and achieves a notable decrease in emissions for scenarios with fossil-based sources and permanent storage (SN.3). The standout is the negative emissions achieved in SN.4 (-21,681 tons), which highlights the effectiveness of OCCS when paired with renewable sources and permanent storage. For HFO, emissions remain highest without permanent storage (SN.5) and are substantially reduced when OCCS is used with permanent storage (SN.6), suggesting the benefits of integrated carbon management strategies.

The scenario with a 90% capture rate reinforces the significant benefits of high carbon capture levels. Methanol from renewable sources (SN.2) achieves complete emission neutralization, while emissions from fossil-based sources with permanent storage (SN.3) are greatly reduced. Although OCCS and permanent storage (SN.6) lower HFO emissions, the persistent emissions underscore the need for a shift to renewable energy. This detailed analysis across varying carbon capture rates paints a compelling picture for the maritime industry, advocating for a move towards renewable energy and enhanced carbon capture and storage technologies. Such a transition is crucial for the sector to not only achieve carbon neutrality but also to potentially reach carbon negativity, a step in alignment with global climate mitigation efforts. The findings emphasize the necessity for refined GHG accounting frameworks to accurately direct the industry's sustainable evolution.

8.3.3 Comparison of WtW GHG emissions

The analysis of WtW emission data from various carbon capture scenarios reveals a clear correlation between the rate of carbon capture and the resulting WtW emissions for methanol and HFO across different feedstocks. At the baseline carbon capture rate of 35%, as depicted in Figure 8-10, WtW emissions for methanol from black liquor with OCCS without permanent storage (Scenario SN.2) are 38.44 CO_2 eq./MJ. This figure decreases to 13.85 CO_2 eq./MJ at a 50% capture rate with permanent storage (Scenario SN.4), as shown in Figure 8-10. Remarkably, as depicted in Figure 8-12, at a 90% capture rate, the emissions for the same feedstock under Scenario SN.4 fall to -24.08 CO_2 eq./MJ, transitioning from positive to negative emissions, demonstrating the significant environmental benefits of higher capture rates coupled with permanent storage. This benefit is even more pronounced with waste CO_2 feedstock, where emissions plummet to -128.78 CO_2 eq./MJ under Scenario SN.4 at a 90% capture rate, highlighting the transformative impact of combining high capture rates with permanent storage solutions.

For fossil-based feedstocks like coal, the baseline WtW emissions without permanent storage (Scenario SN.1) are substantial at 159.04 CO_2 eq./MJ and are only marginally reduced to 134.44 CO_2 eq./MJ with permanent storage (Scenario SN.3). Even with a 90% capture rate, emissions for Scenario SN.3 decrease to 96.27 CO_2 eq./MJ, underscoring that negative emissions are unachievable without transitioning to renewable feedstocks.

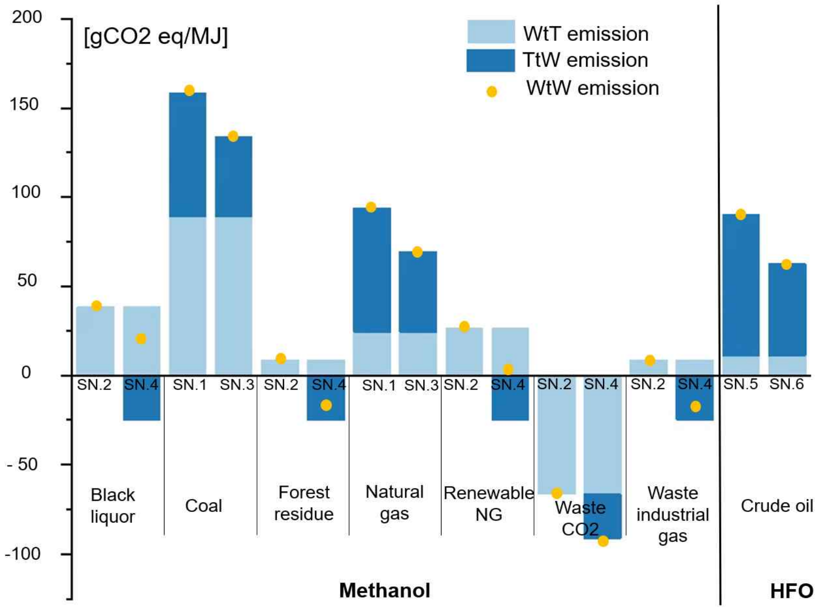


Figure 8-10 WtW GHG emissions and carbon intensity at baseline carbon capture rates with utilization of available exhaust gas heat

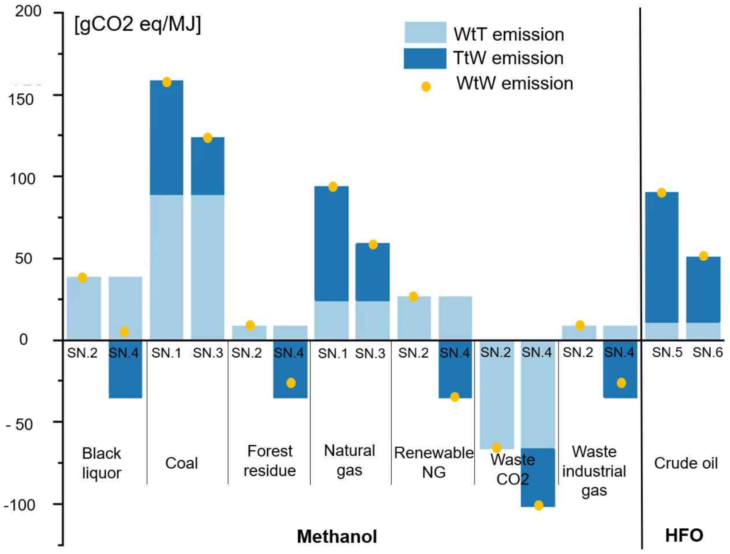


Figure 8-11 WtW GHG emissions and carbon intensity at 50% carbon capture rate

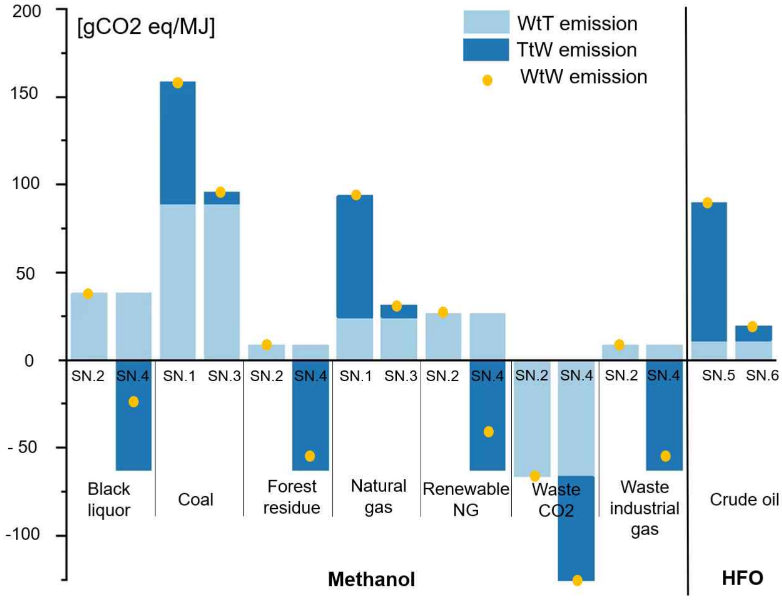


Figure 8-12 WtW GHG emissions and carbon intensity at 90% carbon capture rate

The analysis underscores the critical influence of feedstock type, carbon capture rate, and storage methods on the life cycle GHG emissions of marine fuels. It is apparent that higher carbon capture rates markedly reduce the carbon footprint of all fuels. However, the goal of achieving negative emissions is only viable with renewable feedstocks coupled with permanent storage. The findings indicate that while OCCS is an effective means to lower emissions, their success greatly depends on the carbon source. Fossil fuels, even with high capture rates, yield a net positive emission due to their inherently non-renewable nature. Conversely, renewable feedstocks, particularly when integrated with OCCS and permanent storage, have the potential not only to mitigate but to reverse the trajectory of emissions, thereby contributing to the reduction of atmospheric CO_2 levels.

8.3.4 The impact on the proposed accounting framework

From an analysis of operational data for the 49 case ships with four ship types, Figure 8-13 shows the attained CII with OCCS and no OCCS compared to the 2023 required CII target within the existing ship energy efficiency framework when baseline carbon capture rates (35%) with utilization of available exhaust gas heat is applied. As can be seen, the attained CII with OCCS was significantly lower than the attained CII without OCCS, and both were below the 2023 required CII target. For LNG Carriers, the attained CII with OCCS consistently surpasses the 2023 requirements by a significant margin, whereas without OCCS, the attained CII often falls short of the required targets. This trend is similarly observed in gas carriers and tankers, where the application of OCCS results in a substantive decrease in carbon intensity, thereby exceeding the mandated benchmarks. Bulk carriers also demonstrate improved CII with OCCS; however, the margin of surpassing the required targets is not as pronounced as it is with LNG and gas carriers.

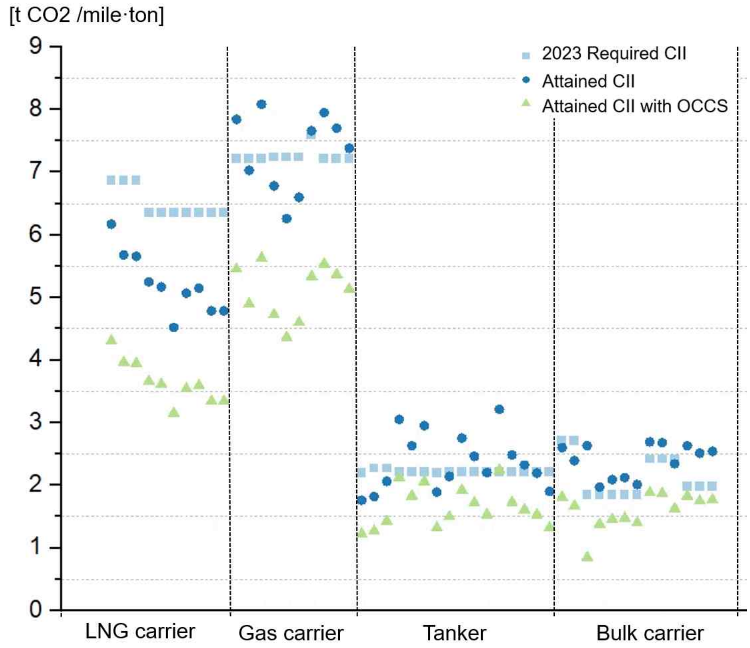


Figure 8-13 Attained CII with OCCS and no OCCS compared to 2023 required CII target

Figure 8-14 to Figure 8-16 illustrate the projected changes in CII ratings for 49 case study ships under various scenarios. The projections outlined in Table 8-9- detailing incrementally stringent CII targets up to 2030 - provide the context for Figure 8-14 which shows the annual distribution of the ships' CII ratings, projected from their current operational data through to 2030. The analysis indicates that a significant majority, approximately 70%, of the fleet would fall within the suboptimal CII categories D or E. Conversely, only about 10% are projected to achieve a superior CII rating of A or B. This notable discrepancy implies that without considerable enhancements in energy efficiency, most of the selected ships are poised to not meet the IMO CII targets for 2030.

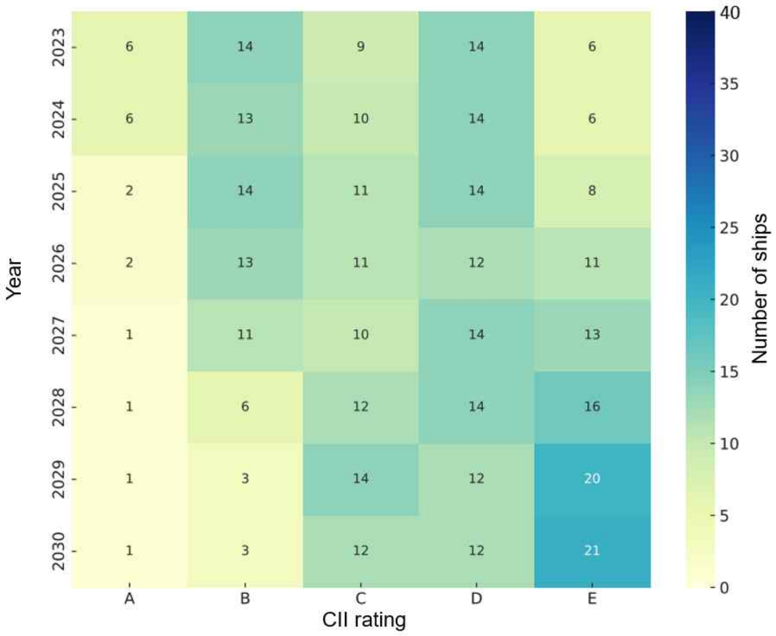


Figure 8-14 Projected CII ratings for case ships under constant operational conditions until 2030

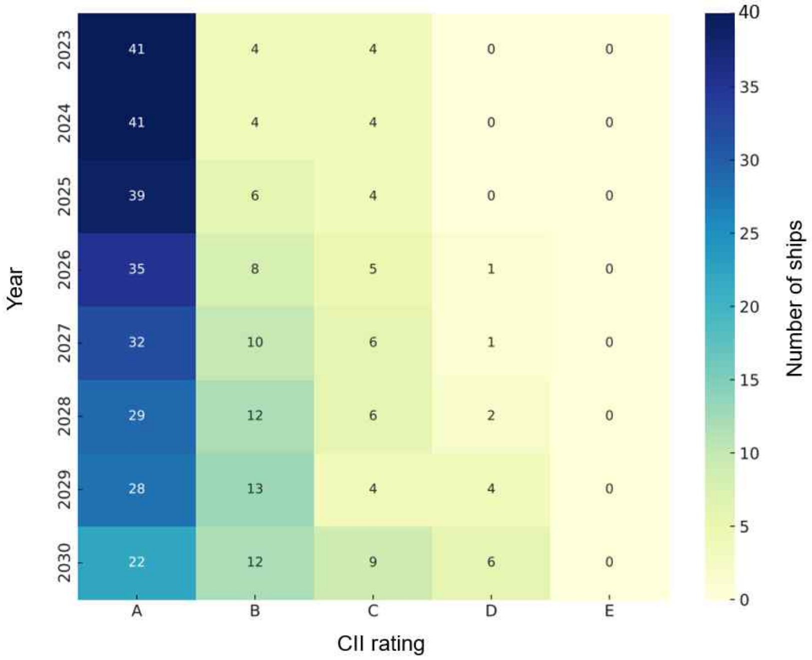


Figure 8-15 Projected CII ratings for case ships with OCCS implementation under the current regulatory framework

Figure 8-15 displays the projected CII ratings for the case study ships, assuming the implementation of OCCS and constant operational conditions up to 2030, within the existing regulatory context detailed in Section 8.2.7. Notably, with an assumed 35% capture rate by the OCCS, ships are able to attain an A rating. However, under current regulations, the OCCS's impact is not reflected in the CII ratings, since the existing framework does not account for CO_2 emissions reductions achieved through OCCS. As a result, ships with OCCS installed would continue to be classified within the less favorable D or E categories.

Conversely, as demonstrated in Figure 8-16, the introduction of the proposed framework marks a significant enhancement in CII ratings across the fleet. There is a notable rise in the proportion of ships receiving A or B ratings, increasing from 10% to 41%, and the elimination of D or E ratings. This indicates that the proposed regulatory adjustments could effectively enable ships to not only meet but potentially exceed the IMO's CII targets for 2030 and onwards.

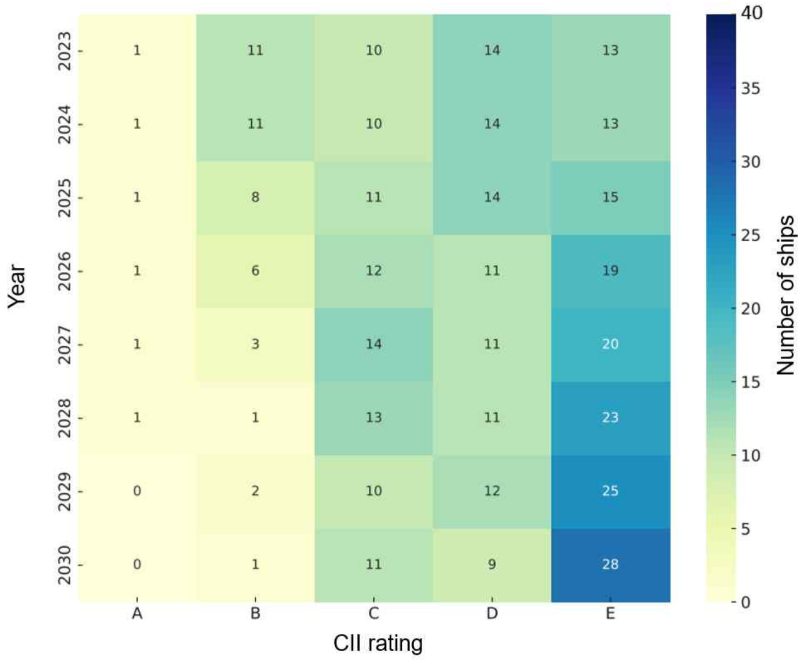


Figure 8-16 Projected CII ratings for case ships with OCCS implementation under the proposed framework

Lastly, the analysis presented underscores the crucial role of effective carbon accounting frameworks in achieving environmental targets in the maritime industry. The current findings highlight a significant disparity between the actual environmental benefits of OCCS and their recognition within the existing regulatory framework. This discrepancy poses a critical challenge in accurately assessing and incentivizing the adoption of carbon reduction technologies. The data suggests that while OCCS can substantially improve the CII of ships, the current regulatory mechanisms fail to adequately capture these improvements. Consequently, there is an urgent need for regulatory bodies, particularly the International Maritime Organization (IMO), to revise the existing frameworks to better reflect the advancements in carbon capture and emission reduction technologies.

Furthermore, the projected shift in CII ratings under the proposed framework opens a new vista in maritime environmental policy. The increase in the number of ships achieving A or B ratings from 10% to 41% is not just a quantitative change but a qualitative leap towards more sustainable maritime operations. This transition could serve as a catalyst for broader change within the industry, encouraging the adoption of green technologies and the revaluation of operational practices. It also suggests that with the right regulatory support and technological advancements, the maritime sector can not only meet but also surpass the stringent CII targets set for 2030 and beyond.

8.4 Chapter summary and conclusions

The chapter outlines critical insights into GHG emissions accounting for international shipping, focusing on methanol and highlighting the effectiveness of OCCS:

- Renewable feedstocks and carbon capture technologies significantly reduce WtT and WtW GHG emissions for methanol, demonstrating the importance of sustainable carbon sourcing and advanced carbon management strategies in maritime fuel production. High carbon capture rates, particularly with renewable sources, can drastically lower emissions, showcasing the potential for methanol production pathways to transition from positive to negative emissions.

- The implementation of OCCS plays a pivotal role in reducing TtW GHG emissions and GHG intensity for both methanol and HFO, emphasizing its capacity to support the maritime industry's shift towards carbon neutrality. Analysis of carbon capture scenarios illustrates that OCCS effectiveness increases with the capture rate, offering a substantial contribution towards achieving net-zero emissions in the industry.

- The attained CII with OCCS implementation significantly surpasses the 2023 required CII targets, highlighting OCCS's potential to enhance ships' environmental performance. Yet, current regulatory frameworks do not fully recognize the CO2 reductions achieved through OCCS, leading to a discrepancy in CII ratings. Projections indicate that without significant enhancements in energy efficiency or regulatory changes, the majority of the fleet risks not meeting the IMO CII targets for 2030.

- The proposed accounting framework, integrating OCCS and emphasizing renewable energy sources, promises a notable improvement in ships' CII ratings, aligning with and potentially exceeding future environmental targets. This underscores the urgent need for regulatory bodies to revise existing frameworks to better reflect advancements in carbon capture and emission reduction technologies, facilitating the maritime sector's sustainable evolution.

9 DISCUSSION

9.1 Academic novelty in the enhanced LCA framework

The shipping industry's decarbonization is vital to addressing global climate change. Traditionally, the industry has concentrated on GHG emissions from ship operations. However, adopting a life cycle approach to assess GHG emissions from ship fuel-including both fuel use and upstream emissions-has emerged as an effective policy tool to encourage low-carbon and zero-carbon fuels. Policymakers must grasp the current WtW emissions, particularly from fossil fuels, to set informed GHG reduction targets.

The findings of this thesis propose a new benchmark for evaluating the impact of renewable fuels to be introduced, enhancing the assessment of policy efficacy over time. Significant differences in upstream emissions have been highlighted, even with the same fossil-based fuels, as illustrated in Figure 9-1. The research presents a Sankey diagram that serves as a robust tool for estimating current emission levels from fossil fuel use and the potential reductions achievable with mature technologies.

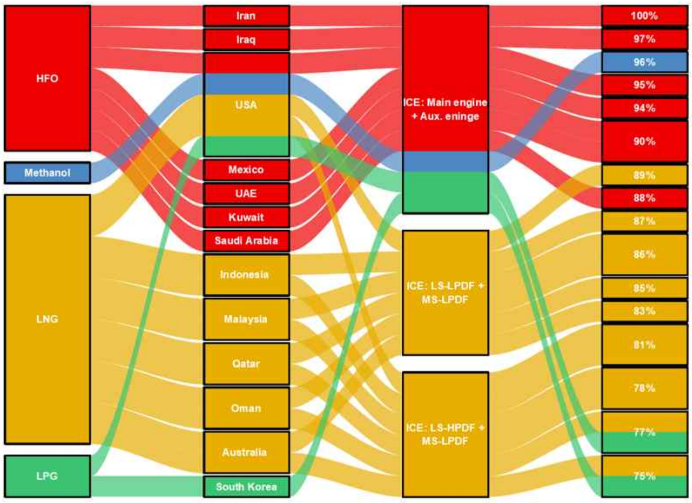


Figure 9-1. The pathway of life cycle GHG emission for marine fuels imported to South Korea

From an import-dependent country's standpoint, like South Korea, the adoption of alternative fuels in international shipping also signifies a reduction in GHG emissions from fuel transportation. The measurement of GHG emissions by international maritime transportation as a fraction of the total WtW emissions enables an understanding of how shipping decarbonization contributes to WtW emissions for domestically produced marine fuels.

Despite numerous studies comparing the life cycle GHG emissions of conventional and alternative fuels, a consensus on integrating low-emission fuels into international shipping to meet reduction goals is still lacking. Addressing this, the study investigates sustainable fuel pathways, focusing on hydrogen-based e-fuels and related engine technologies. A proposed prospective LCA framework analyzed GHG emissions across various scenarios, accounting for technological progress in WtT and TtW processes and projected fleet sizes for 2030, 2040, and 2050.

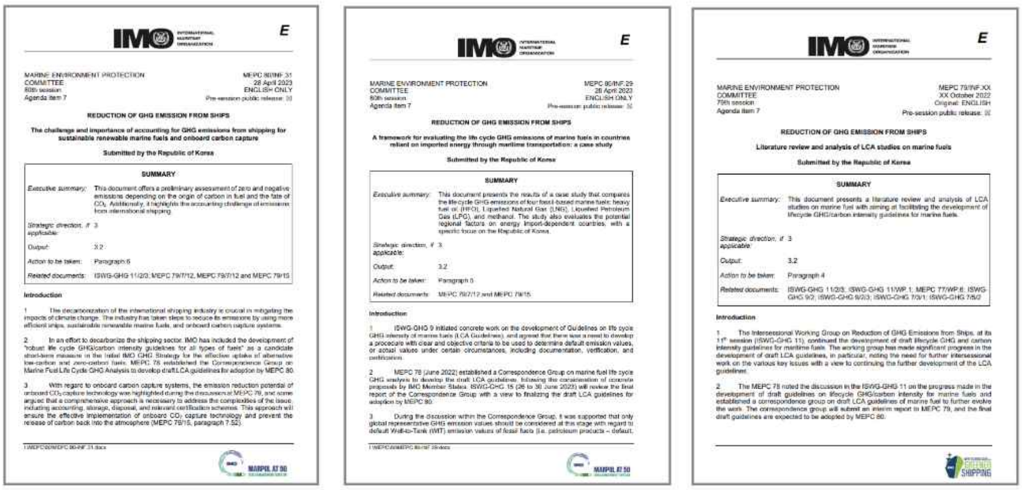
Emphasis is placed on factors such as transport demand, scrapping rates, and the effects of regulatory measures like the Carbon Intensity Indicator (CII) and the Energy Efficiency Existing Ship Index (EEXI). The assessment considers the expected reductions in operational speed and their effects on GHG emissions and the potential demand for additional ships.

For import-dependent countries targeting net-zero life cycle emissions, even with renewable fuel sources, challenges persist. For instance, maritime transport of liquified hydrogen, if reliant on conventional fuels, significantly contributes to WtT emissions. The insights from the study encourage governmental actions towards GHG emission reduction in marine fuels, considering various fuel options. Strategies like 'green shipping corridors' are essential for promoting alternative fuel production, distribution, and usage, thus supporting sustainable marine fuel practices.

Although the thesis primarily examines the use of e-fuels in shipping, the developed framework has wider implications. Extending this LCA approach to other transport sectors could provide policymakers with strategies to enhance renewable resource use, leading to further reductions in life cycle GHG emissions and fostering the transition to sustainable, renewable fuels.

9.2 Original contribution to industry by suggesting the LCA regulatory framework for marine fuels

In response to the urgent need for decarbonization in international shipping, the IMO has embarked on formulating LCA guidelines for current and prospective marine fuels, aiming to boost the uptake of cleaner alternatives. This endeavor has necessitated a detailed examination of prior LCA studies on marine fuels, evaluation of existing regional policies, and analysis of methodologies from other sectors. Key harmonization areas within the LCA regulatory framework were identified from this research. The findings underscore the IMO's commitment to refining the LCA framework for marine fuels, providing actionable solutions and recommendations. A major contribution of this work was the presentation of these research outcomes to the IMO policymakers at the 79th Marine Environment Protection Committee (MEPC) session, as depicted in Figure 9-2.



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MARINE ENVIRONMENT PROTECTION
COMMITTEE
80th session
Agenda item 7

MEPC 80/INF.31
28 April 2023
ENGLISH ONLY
Pre-session public release: ☒

REDUCTION OF GHG EMISSION FROM SHIPS

The challenge and importance of accounting for GHG emissions from shipping for sustainable renewable marine fuels and onboard carbon capture

Submitted by the Republic of Korea

SUMMARY

Executive summary:	This document offers a preliminary assessment of zero and negative emissions depending on the origin of carbon in fuel and the fate of CO_2. Additionally, it highlights the accounting challenge of emissions from international shipping
Strategic direction, if applicable:	3
Output:	3.2
Action to be taken:	Paragraph 6
Related documents:	ISWG-GHG 11/2/3, MEPC 79/7/12, MEPC 79/7/12 and MEPC 79/15

Introduction

1 The decarbonization of the international shipping industry is crucial in mitigating the impacts of climate change. The industry has taken steps to reduce its emissions by using more efficient ships, sustainable renewable marine fuels, and onboard carbon capture systems.

2 In an effort to decarbonize the shipping sector, IMO has included the development of "robust life cycle GHG/carbon intensity guidelines for all types of fuels" as a candidate short-term measure in the Initial IMO GHG Strategy for the effective uptake of alternative low-carbon and zero-carbon fuels. MEPC 78 established the Correspondence Group on Marine Fuel Life Cycle GHG Analysis to develop draft LCA guidelines for adoption by MEPC 80.

3 With regard to onboard carbon capture systems, the emission reduction potential of onboard CO_2 capture technology was highlighted during the discussion at MEPC 79, and some argued that a comprehensive approach is necessary to address the complexities of the issue, including accounting, storage, disposal, and relevant certification schemes. This approach will ensure the effective implementation of onboard CO_2 capture technology and prevent the release of carbon back into the atmosphere (MEPC 79/15, paragraph 7.52).

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MARINE ENVIRONMENT PROTECTION
COMMITTEE
80th session
Agenda item 7

MEPC 80/INF.29
28 April 2023
ENGLISH ONLY
Pre-session public release: ☒

REDUCTION OF GHG EMISSION FROM SHIPS

A framework for evaluating the life cycle GHG emissions of marine fuels in countries reliant on imported energy through maritime transportation: a case study

Submitted by the Republic of Korea

SUMMARY

Executive summary:	This document presents the results of a case study that compares the life cycle GHG emissions of four fossil-based marine fuels: heavy fuel oil (HFO), Liquefied Natural Gas (LNG), Liquefied Petroleum Gas (LPG), and methanol. The study also evaluates the potential regional factors on energy import-dependent countries, with a specific focus on the Republic of Korea.
Strategic direction, if applicable:	3
Output:	3.2
Action to be taken:	Paragraph 5
Related documents:	MEPC 79/7/12 and MEPC 79/15

Introduction

1 ISWG-GHG 9 initiated concrete work on the development of Guidelines on life cycle GHG intensity of marine fuels (LCA Guidelines), and agreed that there was a need to develop a procedure with clear and objective criteria to be used to determine default emission values, or actual values under certain circumstances, including documentation, verification, and certification.

2 MEPC 78 (June 2022) established a Correspondence Group on marine fuel life cycle GHG analysis to develop the draft LCA guidelines, following the consideration of concrete proposals by IMO Member States. ISWG-GHG 15 (26 to 30 June 2023) will review the final report of the Correspondence Group with a view to finalizing the draft LCA guidelines for adoption by MEPC 80.

3 During the discussion within the Correspondence Group, it was supported that only global representative GHG emission values should be considered at this stage with regard to default Well-to-Tank (WtT) emission values of fossil fuels (i.e. petroleum products – default,

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MARINE ENVIRONMENT PROTECTION
COMMITTEE
79th session
Agenda item 7

MEPC 79/INF.XX
XX October 2022
Original: ENGLISH
Pre-session public release: ☒

REDUCTION OF GHG EMISSION FROM SHIPS

Literature review and analysis of LCA studies on marine fuels

Submitted by the Republic of Korea

SUMMARY

Executive summary:	This document presents a literature review and analysis of LCA studies on marine fuel with aiming at facilitating the development of lifecycle GHG/carbon intensity guidelines for marine fuels.
Strategic direction, if applicable:	3
Output:	3.2
Action to be taken:	Paragraph 4
Related documents:	ISWG-GHG 11/2/3; ISWG-GHG 11/WP.1; MEPC 77/WP.8; ISWG-GHG 9/2; ISWG-GHG 9/2/3; ISWG-GHG 7/3/1; ISWG-GHG 7/5/2

Introduction

1 The Intersessional Working Group on Reduction of GHG Emissions from Ships, at its 11th session (ISWG-GHG 11), continued the development of draft lifecycle GHG and carbon intensity guidelines for maritime fuels. The working group has made significant progress in the development of draft LCA guidelines, in particular, noting the need for further intersessional work on the various key issues with a view to continuing the further development of the LCA guidelines.

2 The MEPC 78 noted the discussion in the ISWG-GHG 11 on the progress made in the development of draft guidelines on lifecycle GHG/carbon intensity for marine fuels and established a correspondence group on draft LCA guidelines of marine fuel to further evolve the work. The correspondence group will submit an interim report to MEPC 79, and the final draft guidelines are expected to be adopted by MEPC 80.

Figure 9-2 Contributions to the LCA Regulatory framework for marine fuels - examples from IMO submissions

Countries that rely on energy imports, such as South Korea, have faced a dearth of reliable life cycle emission data for marine fuels, often depending on generic databases like GaBi and GREET, which come with their own sets of assumptions. Developing a tailored database and accurate emission models became an essential undertaking, providing a foundation for establishing robust policies aimed at reducing GHG emissions in the shipping sector. The efficacy of the proposed emission model has been validated through a comprehensive analysis of data and scenarios tailored to South Korea's specific conditions.

To date, no research has set forth a default value for marine fuel LCA tailored to particular countries or the international shipping sector. This study's insights into the uncertainties and variations caused by geographical differences, supply routes, and methods offer valuable guidance for governments in setting appropriate baselines for life cycle GHG emission regulations across a range of fuel options. Adopting conservative values over average performance in establishing baselines or default values enables operators to present certified actual values, enhancing knowledge and reducing uncertainty. The IMO framework initially employs global default values for fossil fuel pathways in its LCA methodology, with the possibility of adopting regional factors once they stabilize. This research also contributes to the development of regional values where global defaults may be insufficient.

Overall, this study contends that both WtT and TtW emission values should be established using a unified methodology. It introduces a new direction for environmental evaluation from a life cycle perspective, positioning itself as a complement to current regulations focused primarily on operational emissions. By clearly illustrating the significant environmental impacts of various import routes, this research underscores the pressing need for a life cycle evaluation system for ship fuels. The implications of this study are substantial, offering a framework that can be implemented in policy and regulation to enhance LCA application in the maritime sector. While the findings from the South Korean case are instructive, further case studies across different countries are necessary for comprehensive LCA impact assessments. As a pivotal contribution, the research methodologies and results were documented and presented to IMO policymakers during the 80th MEPC session, as depicted in . It is now crucial to consider how the proposed methods and models can be integrated into the evolving IMO LCA guidelines.

Meanwhile, the IMO has adopted a 2023 GHG strategy aiming for net-zero GHG emissions by around 2050. This ambitious target underscores the importance of technological advancements and the widespread adoption of zero or near-zero GHG emission technologies, fuels, and energy sources in international shipping. According to the revised IMO GHG strategy, alternative fuels should account for at least 5%, ideally 10%, of the total energy used in international shipping by 2030. Additionally, the strategy aims to reduce total annual GHG emissions from international shipping by at least 20%, ideally 30%, by 2030 compared to 2008 levels. However, the application of the framework proposed in this study indicates that achieving a 20-30% reduction from the 2008 baseline is a significant challenge. Even if near-zero emission fuels like ammonia were to constitute 10% of the energy mix, achieving this target seems formidable, as illustrated in Figure 9-3. Moreover, under scenarios of high transport demand growth, our projections suggest that total annual GHG emissions in 2030 could surpass those of 2022. This possible increase reinforces the need for a significant enhancement in the integration of zero or near-zero GHG emission fuels in the next revision of the IMO GHG strategy. Additionally, detailed quantification and strategic commitments from a broad range of stakeholders will be crucial to meeting the ambitious targets set by the IMO.

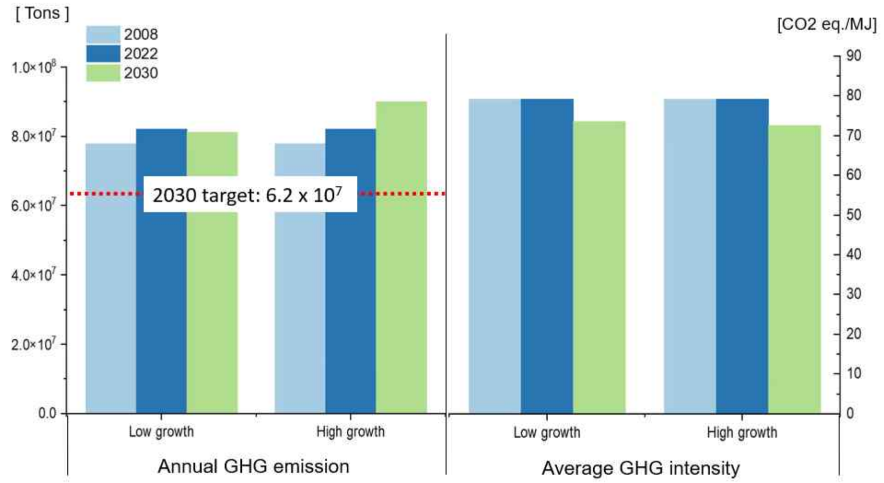

Figure 9-3 Estimated annual GHG emissions and intensity from 10% ammonia uptake in the selected fleet

This study addresses this necessity by proposing a framework that assesses the potential contribution of integrated sustainable fuels towards meeting the GHG emission reduction targets mandated by international shipping regulations. The proposed framework could serve as a standardized LCA methodology, enhancing current models to ensure alignment with both national and international regulations.

In terms of effectively accounting for GHG emissions from international shipping, our case study highlights the crucial role of feedstock in determining the environmental impact of marine fuels, particularly in relation to life cycle GHG emissions. The marked contrast in emissions between renewable and fossil feedstocks underscores the urgency of transitioning towards more sustainable energy sources. This shift, essential for environmental sustainability, aligns with global climate change mitigation goals and marks a significant stride toward the decarbonization of the shipping industry.

The analysis of operational data from the case ships across various scenarios sheds light on the substantial impact of onboard carbon capture systems (OCCS) in reducing GHG emissions. However, the current regulatory framework does not sufficiently recognize the emission reductions achieved through OCCS, as evidenced by the persistently low Carbon Intensity Indicator (CII) ratings within the existing system. This gap between the actual emission reductions and their recognition in the regulatory framework highlights a critical deficiency in the current GHG accounting methods. A significant contribution of this study was presenting these findings to IMO policymakers at the 80th Marine Environment Protection Committee (MEPC) session.

Moreover, the projected CII ratings under different scenarios indicate a concerning trend: a considerable portion of the fleet is likely to fall short of meeting the IMO's 2030 CII targets. This situation signals the need for greater advancements in energy efficiency and the adoption of green technologies in the maritime sector. Nonetheless, the introduction of the proposed accounting framework, which more effectively accounts for OCCS and renewable feedstocks, suggests a viable way forward. The notable increase in ships achieving higher CII ratings under this new framework implies that, with the right regulatory support and technological advancements, the shipping industry could meet and possibly surpass future GHG reduction targets.

Our case study underscores the necessity for a paradigm shift in the regulatory accounting of GHG emissions in international shipping. By adopting more nuanced and comprehensive accounting methods that accurately reflect the benefits of sustainable fuels and technologies such as OCCS, the industry can significantly progress toward decarbonization. The results call for a strategic shift towards renewable energy sources and the enhancement of carbon capture technologies, thereby positioning the maritime sector to substantially reduce its environmental impact and contribute effectively to global climate change mitigation efforts. The insights from this study are instrumental in steering the shipping industry towards sustainable practices, ensuring alignment with the broader goals of climate change mitigation.

9.3 Limitation and directions for future study

This study emphasizes that decarbonization relies not solely on the adoption of alternative fuels but also on the integration of renewable energy into their production processes. Consequently, future research should concentrate on enhancing the use of renewable energy within fuel production pathways, scaling up Direct Air Capture (DAC) technologies, and transitioning from fossil-based to renewable energy sources, all of which are critical for advancing the decarbonization of the international shipping industry.

The study's focus on particular case ships or the bulk carrier fleet narrows the broader applicability of its findings to the international shipping sector. A more comprehensive assessment could be achieved by applying the proposed framework to a variety of vessel types, thereby offering a broader view of sustainable fuel integration across the international shipping industry. Additionally, while this study does not address external factors such as fuel costs and market competition, these elements are crucial for understanding fuel adoption and warrant in-depth investigation in future research. Furthermore, the role of biofuels, including their introduction and blending, represents a significant aspect of decarbonizing international shipping. However, given this study's exclusive focus on e-fuels, additional research is necessary to examine various scenarios that incorporate both biofuels and e-fuels, utilizing the framework established in this study.

Furthermore, the projected GHG emissions in this study are based on emission factors that carry inherent uncertainties, especially for emerging engine technologies. The technical maturity of ammonia-fueled engines and their N_2O emissions, for instance, remain uncertain. Consequently, future research should explore the effectiveness of emission control technologies, such as Selective Catalytic Reduction (SCR) systems.

The research approach used in this study provides an essential baseline for understanding the distribution of fuel mixes and their potential evolution. However, it may simplify complex scenario modelling, thus necessitating a careful interpretation of the projected trends for 2030 and 2050. The exclusion of specific scenarios, such as fuel mixes in fleet modelling and emission estimates, could lead to an underestimation of GHG reduction possibilities with alternative fuels in current fleets.

The GHG intensity of regional electricity production significantly affects emissions from hydrogen-based e-fuels, and it is crucial to these models. This intensity is influenced by the varied energy policies across nations. For example, the difference within Europe - from Poland's high carbon intensity at 986 gCO_2eq./kWh to Norway's low at 20 gCO_2eq./kWh (Wernet et al., 2016) - underscores the need for regional considerations in future assessments.

Additionally, the dependence of renewable energy sources, such as wind and photovoltaic (PV), on geographic and environmental factors poses a limitation. A deeper understanding of these dependencies and more comprehensive assessments of regional impacts—including actual production areas, transportation routes, and the availability of renewable sources—are advisable. Furthermore, while it is beyond the scope of this study, addressing the issue of the additional energy required to produce e-fuels is essential for assessing their feasibility and sustainability.

This study integrated data from various sources based on data availability. Before referencing Greenhouse Gas (GHG) emissions data, a meticulous examination of the underlying assumptions was undertaken, and the most reliable values were utilized to mitigate potential disparities and uncertainties. Nevertheless, it is crucial to recognize that, despite these efforts, inherent challenges persist in fully eradicating variations across datasets. The significance of transparency in identifying and addressing potential biases during the data integration process should be emphasized. Additionally, sensitivity analysis and robust uncertainty treatment should be considered.

10 CONCLUSIONS

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

1) The study identified significant gaps in current policies and LCA methodologies concerning GHG reduction from marine fuels. It highlighted the pressing need for a unified LCA framework to ensure consistent and reliable GHG emissions data within the shipping industry. Essential areas for harmonization include GHG emissions scope, global warming potential metrics, functional units, LCA databases, and allocation methods. In doing so, unequivocal LCA guidelines with unified, harmonised methodologies are indispensable to preclude inception of a uncertain landscape in the shipping industry and support informed decision-making. Indeed, the urgency of the issue cannot be overstated.

2) An advanced LCA framework was successfully developed, tailored to the shipping sector's decarbonization needs. This enhanced framework stands as a significant academic contribution, incorporating comprehensive life cycle considerations and providing a pragmatic structure for industry application.

3) The efficacy of the proposed LCA framework was validated through a series of case studies, with a special focus on the South Korean maritime sector. The case study on hydrogen-based e-fuels demonstrated that the proposed prospective LCA framework effectively predicts the alignment of international shipping's GHG emissions with existing targets and assists in setting future emission targets.

4) In developing the robust default WtW emission values and evaluating the GHG performance of various marine fuels across the world, 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.

5) Proposed GHG emission accounting framework on sustainable marine Fuel and onboard carbon capture system enhances the precision of emission accounting and supports the transition toward a more sustainable and decarbonized shipping sector.

6) The study culminates in offering targeted recommendations for refining LCA regulatory and political frameworks. These recommendations are poised to inform both local and global decarbonization strategies in the shipping sector, highlighting the necessity for international collaboration and policy coherence.

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PUBLICATIONS

IMO documents

- ISWG-GHG 7/5/3 Approaches to be considered in future work on “well-to-propeller” emission information
- MEPC 78/7/13 Measurement of actual methane slip in terms of Tank-to-Wake emission factors by using the relevant procedures in the NOx Technical Code 2008
- MEPC 79/INF.31 Literature review and analysis of LCA studies on marine fuels
- MEPC 80/INF.29 A framework for evaluating the life cycle GHG emissions of marine fuels in countries reliant on imported energy through maritime transportation: a case study
- MEPC 80/INF.31 The challenge and importance of accounting for GHG emissions from shipping for sustainable renewable marine fuels and onboard carbon capture
- MSC 102/21/20 Comments on document MSC 102/21/1 “Proposal for a new output to conduct a focused review of the International Code for the Construction and Equipment of Ships Carrying Liquified Gases in Bulk (IGC Code)”

Conferences

- IMO Presentation at IMO MEPC 80 : Assessment of life cycle GHG emissions of marine fossil fuels : A case study of South Korea (3 July 2023)
- Informal Discussion session on life cycle GHG/Carbon intensity guidelines for marine fuel: Approaches to be considered in future work on “well-to-propeller” emission information (14 to15 April 2021)
- 2022 Smart & Green Energy Maritime Conference “IMO LCA guideline for marine fuels : An overview and current status”
- International Symposium on Marine Engineering and Technology 2021 (ISMT 2021) “Well-to-Wake analysis on greenhouse gas emission of marine fuel in south Korea : conventional fuel, LPG and LNG fuel”

- EKC (Europe-Korea Conference on Science and Technology) 2021 “Current status of development of life cycle GHG/carbon intensity guidelines for marine fuels in IMO”

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- **Ha, S,** Jeong, B., Jang, H., Park, C.*, & Ku, B. (2023). 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. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2023.165366
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- **Ha, S.**, Jeong, B.* and Park, C. (2022). A novel approach to developing effective maritime regulations: The case of LNG cargo filling limits. Journal of International Maritime Safety, Environmental Affairs, and Shipping, 6(4), pp.167-184. https://doi.org/10.1080/25725084.2022.2146374
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- Journal article of “The Motorship” : Discrepancies between IGF and IGC Codes could cause confusion (13 June 2022) https://www.motorship.com/regulation/discrepancies-between-igf-and-igc-codes-could-cause-confusion/1473598.article

A. Appendix : List of LCA studies on the marine fuel

Table A-1 List of LCA studies on the marine fuel

Author(s) and publication date	Type of Fuels	GHG emission Scope	Global warming potential	Sustainability Criteria except for GHG	Functional Unit	life cycle inventory database/tool
(Strazza et al., 2010)	Methanol, Bio-methanol, LNG, Hydrogen in Solid Oxide Fuel Cells (SOFC)	CO_2, CH_4, and N_2O	GWP 100	ODP, POCP, AP, EP	kg CO2eq per kWh (electricity)	SimaPro
(Bengtsson et al., 2011)	HFO, MGO, LNG, GTL(gas-to-liquid)	CO_2, CH_4, and N_2O	GWP 100	AP, EP	t CO2eq per 1 t cargo transported 1 km with a ro–ro vessel	ELCD, JEC
(Bengtsson et al., 2012)	HFO, MGO, Rapeseed methyl ester (RME), Synthetic bio-diesel (BTL), LNG, Bio-LNG	CO_2, CH_4, and N_2O	GWP100	AP, EP, Agricultural land use, Primary energy use, and PM	g CO2eq /MJ fuel: emission factors for the engines on the ro-pax ferries based on the yearly fuel consumption corresponding to energy content	ELCD, JEC
(Brynolf et al., 2014)	HFO, LNG, Methanol, bio-LNG, Bio-methanol	CO_2, CH_4, and N_2O	GWP100	PM, POCP, AP, EP	1 t cargo transported 1 km with a ro-ro vessel (g CO2eq/t km)	ELCD, JEC
(Bicer and Dincer, 2018)	HFO, Hydrogen, Ammonia	CO_2, CH_4, and N_2O	GWP 500	ADP, AP, ODP Ecotoxicity Potentials	g CO2eq emission per tonne-kilometre cruise travel where the functional unit is 1 tonne-kilometre.	GREET
(Gilbert et al., 2018)	HFO, MDO, LNG, Hydrogen, Methanol, Bio-LNG, Bio-diesel	CO_2, CH_4, and N_2O	GWP 100	Air quality (NOx, SOx, PM)	g CO2eq emission/kWh delivered to the shaft	Ecoinvent, ELCD

Author(s) and publication date	**Type of Fuels**	**GHG emission Scope**	**Global warming potential**	**Sustainability Criteria except for GHG**	**Functional Unit**	**life cycle inventory database/tool**
(El-Houjeiri et al., 2019)	HFO, MGO, LNG	CO_2, CH_4, and N_2O	GWP100 & GWP 20	(GWP only)	g CO2eq per 1 kWh of energy transferred to the ship propeller	Oil Production Greenhouse Gas Emissions Estimator (OPGEE), GREET
(Hwang et al., 2019)	HFO, MGO, LNG	CO_2, CH_4, and N_2O	GWP100	AP, PM, POCP, EP	CO2eq emission per the supply and consumption of LHV(MJ) of fuel	Gabi
(Thinkstep, 2019)	HFO, LSFO, MGO, LNG	CO_2, CH_4, and N_2O	GWP20 & GWP 100	Air quality (NOx, SOx, PM)	CO2eq emission per 1 kWh brake power specific unit (g CO2-eq/kWh)	GREET
(Sharafian et al., 2019)	HFO, LNG	CO_2, CH_4, and N_2O	GWP 100	Air quality (NOx, SOx)	CO2eq emissions per kWh engine output	GREET
(Winebrake et al., 2019)	MDO, Methanol, LNG	CO_2, CH_4, and N_2O	GWP 20 & GWP 100	Air quality (NOx, SOx, PM)	mass per energy units (e.g., g/MJ) with engine efficiency	GREET /TEAMS
(Lindstad and Rialland, 2020)	HFO, LSFO, MGO, LNG	CO_2, CH_4, and N_2O	GWP 20 & GWP 100	(GWP only)	CO2eq emissions per kWh as a function of fuel and engine	Gabi, GREET, JRC
(Perčić et al., 2020)	Methanol, Dimethyl ether, LNG, Hydrogen, Biodiesel, Electricity	CO_2, CH_4, and N_2O	GWP 100	(GWP only)	tons of CO2-eq.	GREET
(Spoof-Tuomi and Niemi, 2020)	MDO, LNG, Bio-LNG	CO_2, CH_4, and N_2O	GWP 100	AP, EP, PM, human health	CO2eq g/MJ fuel with engine efficiency	Literature review
(Seithe et al., 2020)	HFO, LNG	CO_2, CH_4, and N_2O	GWP 100	(GWP only)	CO2eq emission per "1 t of cargo transported for 1 km (1 tkm)" and "1 passenger transported for 1 km (1 pkm)"	ELCD, Ecoinvent

Author(s) and publication date	Type of Fuels	GHG emission Scope	Global warming potential	Sustainability Criteria except for GHG	Functional Unit	life cycle inventory database/tool
(Pavlenko et al., 2020)	HFO, LSFO, MGO, LNG	CO_2, CH_4, and N_2O	GWP 20 & GWP 100	(GWP only)	CO2eq emission per shaft work produced by the engine (g/kWh)	GREET
(Manouchehrinia et al., 2020)	LNG	CO_2, CH_4, and N_2O	GWP 100	(GWP only)	-	GREET, GHGenius
(Jang et al., 2021)	HFO, LNG	CO_2, CH_4, and N_2O	GWP 100	AP, EP	CO2eq emission per unit of fuel energy (g/MJ fuel)	Literature review
(Comer and Osipova, 2021)	HFO, LSFO, MGO, LNG	CO_2, CH_4, N_2O and Black carbon	GWP 20 & GWP 100	(GWP only)	CO2eq emission per the mass of fuel the ship consumed	GREET
(Bilgili, 2021a)	Biogas, Dimethyl ether, Ethanol, LNG, LPG, Methanol, Ammonia, Bio-diesel	CO_2, CH_4, and N_2O	GWP 20, GWP 100, GWP 1000	human health, ecosystem, resource utilization, emission inventory	CO2eq emission per 1 ton or the equivalent volume of fuel	SimaPro
(Malmgren et al., 2021)	Bio-methanol, Fossil methanol, Electro-methanol (eMeOH), MGO	CO_2, CH_4, and N_2O	GWP 20, GWP 100	AP, EP, POCP, PM, terrestrial eutrophication	CO2eq emission per a voyage with a RoPax vessel travelling	ELCD
(Fernández-Ríos et al., 2022)	Hydrogen	CO_2, CH_4, and N_2O	GWP 100	HTP,POCP,AP,ADP,ODP ,EP, Ecotoxicity Potentials	CO2eq emission per 1 kWh of energy obtained from the PEMFC and the ICEs systems	Gabi

Note: Ozone layer depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP), Eutrophication Potential (EP), Abiotic depletion Potential (ADP), Human Toxicity Potential(HTP)

B. Appendix : Supplementary material for: 6. A Framework for determining the life cycle GHG emissions of fossil marine fuels in countries reliant on imported energy through maritime transportation

Section 6.3.2.1 (Well-to-Tank Inventory Analysis), Section 6.3.2.2 (Tank-to-Wake Inventory Analysis), Section 6.4.1 (Comparison of WtT GHG emissions from fuels) and 6.4.3(Comparison of WtW GHG emissions)

1. HFO

Table B-1. Summary of imports of crude oil which is base fuel for HFO (Korea Petroleum Association, 2022)

Producing countries	Percentage
Saudi Arabia	27.70%
Kuwait	14.05%
Iraq	11.05%
UAE	8.29%
USA	12.86%
Mexico	4.28%
Iran	3.10%
Russia	2.87%

Table B-2. GHG emissions from oil production and processing for crude oil and HFO

	Ave. GHG emissions (g CO_2eq./MJ) <u>including</u> maritime transportation (Masnadi et al., 2018)	Applied ave. GHG emission value (gCO_2eq/MJ) <u>excluding</u> maritime transportation [2]
Saudi Arabia	5.10	2.56
Kuwait	7.12	4.56
Iraq	14.05	11.44
UAE	7.53	4.97
USA	11.30	8.72
Mexico	9.87	7.29
Iran	17.41	14.79
Russia	9.75	7.17
Average		6.05

OPGEE model adopted using identical default emission value(2.53 g CO_2eq/MJ) for crude oil transportation through ocean tanker with 250,000 tons for carriage and 8,000 miles for operation. In this study, the actual ship operation data from Korean shipping companies was used to estimate the emissions by maritime transportation.

[2] In addition to the exclusion of the default emission value for maritime transportation, the emission values for HFO were sought using the energy-content-based allocation method as shown in B-1, based on specification of petroleum products(Jang and Song, 2015).

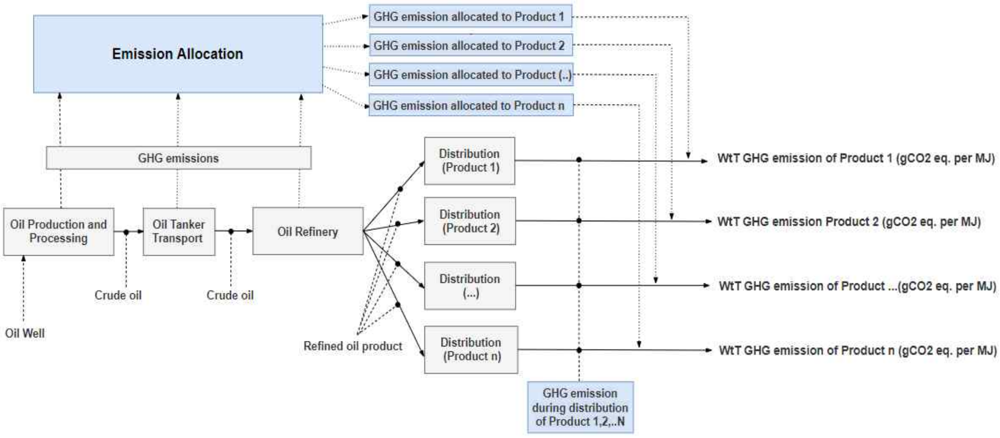


Figure B-1 Outline of the adopted WtT emission allocation model

Table B-3. Ship's Abstract LOG data from Korean shipping companies (300K crude oil tankers)

	Voyages	Ave. mile per voyage	GHG emissions(t CO_2eq)	Cargo carried(t)
Saudi Arabia	7	13324	71247.76	1865722
Kuwait	7	13802	76293.30	1943483
Iraq	1	13263	10784.64	279792

Table B-4. Maritime transport emissions by crude oil tankers

	GHG emission ($gCO_2eq./MJ$)
Saudi Arabia	0.91
Kuwait	0.94
Iraq	0.92
UAE	0.91
USA	2.51
Mexico	2.51
Iran	0.91

The GHG emissions($gCO_2eq./MJ$) of crude oil, LNG(Table B-12) and LPG(Table B-22) during the maritime transportation were estimated with the following equation.

- $Et = \frac{\sum_{i}^{n\ fuel} \sum_{j}^{m\ engine} M_{i,j} \times EF_{GHG}}{M_{cargo}\ x\ LHV}$

- $EF_{GHG} = C_{fCO2} + C_{fCH4}\ x\ GWP_{CH4} + C_{fN2O}\ x\ GWP_{N2O}$

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.

For the study, it was assumed that the values for UAE and Iran were the same as those for Saudi Arabia, which is geographically located similarly. For the USA and Mexico, the values were calculated using the OPGEE model (0.124 gCO_2e/MMBtu-mile) based on a voyage distance of 21,500 miles.

Table B-5. GHG emissions from refining and distribution for HFO based on process-level allocation method (Choi et al., 2020)

Process	GHG emissions ($gCO_2eq./MJ$)
Refining	3.72
Distribution	0.11

Table B-6. Summary of WtT GHG emissions($gCO_2eq./MJ$) for HFO depending on imported countries

	Oil production, processing and transport	Transport by shipping	Refining	Distribution	Total
Saudi Arabia	2.56	0.92	3.72	0.11	7.31
Kuwait	4.56	0.94	3.72	0.11	9.34
Iraq	11.44	0.93	3.72	0.11	16.20
UAE	4.97	0.92	3.72	0.11	9.72
USA	8.72	2.53	3.72	0.11	15.08
Mexico	7.29	2.53	3.72	0.11	13.66
Iran	14.79	0.92	3.72	0.11	19.54
Average	6.05	1.27	3.72	0.11	11.15

In this study, the weighted average WtT GHG emissions associated with imported energy sources or fuels were estimated using the following equation.

- $\text{Average WtT GHG emission} = \frac{\sum_{i}^{n\ countries} (P_i \times \text{WtT}_i)}{\sum_{i}^{n\ countries} P_i}$

where; P_i : the percentage(%) of a specific energy source or fuel imported to South Korea from a particular country, WtT_i : WtT emission value($gCO_2eq./MJ$) of fuels imported from a particular country

2. LNG

Table B-7. Imports of LNG in South Korea (KOGAS, 2020)

Producing countries	Percentage
Qatar	27.00%
Australia	19.00%
USA	14.00%
Malaysia	12.00%
Oman	9.00%
Indonesia	6.00%
Others	13.00%
Total	100.00%

Table B-8. Emission factors used in WtT GHG calculation of LNG (Schuller et al., 2019, US EPA, 2010)

Emissions	Natural gas turbine	Natural gas engine[1]	Diesel fuel engine
CO_2	56.100	54.39	74.06
CH_4	0.0033	0.00483	0.0033
N_2O	0.00116	0.00116	0.00037
gCO_2-eq/MJ	56.50	69.21	74.26

[1] The energy consumption from natural gas was calculated as the total consumption in the natural gas engine when determining GHG emissions, which was applied in this study.

Table B-9. Energy consumptions (KJ/t) and gas losses (Vol.%) for conventional gas production & processing (Schuller et al., 2017, Schuller et al., 2019)

	Electricity	Diesel fuel	Natural Gas	Gas Loss
Malaysia	1180.00	31292.00	875643.00	0.75
Indonesia	952.00	31292.00	4392765.00	0.46
Australia	1162.00	30211.00	539289.00	0.10
Qatar	0.00	0.00	1479673.00	0.06
Oman	0.00	0.00	1479673.00	0.06
USA	20668.00	40320.00	1616026.00	0.10

Table B-10. Energy consumption (KJ/t) and gas losses (Vol.%) for pipe line transportation (Schuller et al., 2017, Schuller et al., 2019)

	Distance	Natural Gas	Gas Loss(Vol.%)
Malaysia	500.00	0.00003	0.06
Indonesia	60.00	0.00003	0.00
Australia	475.00	0.00003	0.00
Qatar	80.00	0.00003	0.00
Oman	80.00	0.00003	0.00
USA	500.00	0.00003	0.24

Table B-11. Energy consumption (KJ/t) for natural gas liquefaction (including purification) (Schuller et al., 2017, Schuller et al., 2019)

	Electricity	Natural Gas
Malaysia	187724	4997131
Indonesia	186754	4996224
Australia	143981	5113905
Qatar	290520	5220150
Oman	290520	5220150
USA	109218	5802591

Table B-12. Maritime transport emissions based on ship's Abstract LOG data from Korean shipping companies

	Voyages	Ave. miles	Cargo carried (t)	Cargo capacity (Propulsions system)	GHG emissions(t CO_2eq)	gCO_2-eq/MJ	gCO_2-eq/t lng & mile
Malaysia	6	5078.37	943,281	125K(steam turbine)	105034.08	2.26	1.22
Indonesia	11	5224.92	575,618	125K(steam turbine)	68677.74	2.43	2.08
Australia	14	9576.79	719,739	125K(steam turbine)	145667.24	4.11	1.51
Qatar	23	13019.48	1,379,282	135K(steam turbine)	405417.96	5.97	0.98
Oman	9	12115.00	536,255	135K(steam turbine)	147557.33	5.59	2.52
USA	15	21336.60	1,015,525	174K(LS-HPDF)	293877.64	5.88	0.90

Table B-13. Energy consumption(KJ/t) and gas losses in LNG terminal operations and bunkering(Research Center of Korea, 2015, Schuller et al., 2019)

Electricity(kJ/t)	Terminal operation (Leakage & venting (g/MJ))	Bunkering(wt.%)
4,456	0.0082	0.0361

Table B-14. Electricity grid mix (Choi et al., 2020, Schuller et al., 2019)

	gCO_2-eq/kJ
Malaysia	0.22
Indonesia	0.25
Australia	0.25
Qatar	0.16
Oman	0.16
USA	0.15
South Korea	0.18

Table B-15. Summary of WtT GHG emissions (gCO_2eq./MJ) for LNG depending on imported countries

	Gas production, processing and pipeline transport	Natural Gas Liquefaction (including Purification)	LNG Carrier Transport	LNG Terminal Operations and Maritime Bunkering	Total
Malaysia	7.46	8.34	2.26	0.49	18.56
Indonesia	9.48	8.45	2.43	0.49	20.85
Australia	2.46	8.40	4.11	0.49	15.46
Qatar	2.70	8.78	5.97	0.49	17.94
Oman	2.70	8.78	5.59	0.49	17.56
USA	5.65	8.98	5.88	0.49	21.01
Average	4.25	8.65	4.76	0.49	18.14

3. LPG

Table B-16 LPG produced in South Korea(KOSIS, 2022)

	Percentage
Crude oil based LPG	25.90%
Natural gas based LPG	74.10%

Table B-17 Oil recovery and transportation (for production of crude-based LPG)

	GHG (gCO_2-eq./MJ)
Recovery	5.49[1]
Transportation by international shipping	1.15[1]

[1] Based on specification of petroleum products for refinery-level allocation(Jang and Song, 2015) and GHG emissions from oil production and its transportation indicated Tables S2 and S4, the emission value was allocated(See Figure S1).

Table B-18 GHG emissions for refining and distribution (Choi et al., 2020)

	CO_2 (gCO_2/MJ)	CH_4 (gCH_4/MJ)	N_2O (gN_2O/MJ)	GHG (gCO_2eq./MJ)
Refining	5.083	0.0061	0.000002	5.237
Distribution	0.34	0.0003	0.000008	0.35

Table B-19 WtT GHG emissions (gCO_2eq./MJ) for crude oil-based LPG (Figure 8)

	Oil production, processing and transport	Oil tanker transport	Refining	Distribution	Total
Crude oil based LPG	5.49	1.15	5.24	0.35	12.23

Table B-20 Imports of natural gas-based LPG (Korea Petroleum Association, 2022)

	Percentage
USA	93.47%
Others	6.53%

Table B-21 GHG emissions (g CO_2 eq./MJ) for natural gas-based LPG production (Choi et al., 2020)

Process	CO_2 (gCO_2/MJ)	CH_4 (gCH_4/MJ)	N_2O (gN_2O/MJ)	GHG (gCO_2 eq./MJ)
Recovery	1.017	0.0795	0.000012	3.01
Processing	2.701	0.042	0.00001	3.75
LPG production	2.501	0.0049	0.000021	2.63

Table B-22 Maritime transport emissions (82K LPG carrier) based on ship's Abstract LOG data from Korean shipping companies

Producing countries	Voyage miles	Cargo carried(ton)	GHG emissions (t CO2eq)	GHG emissions (gCO2 eq./MJ)
USA	21421	46334	9415.98	4.42

Table B-23 GHG emissions (g CO_2 eq./MJ) for distribution (Choi et al., 2020)

CO_2 (gCO_2/MJ)	CH_4 (gCH_4/MJ)	N_2O (gN_2O/MJ)	GHG (gCO_2eq./MJ)
0.281	0.0003	0.000006	0.29

Table B-24 Summary of WtT GHG emissions (gCO_2eq./MJ) for natural gas-based LPG

	Recovery	Processing	LPG production	LPG Carrier Transport	Distribution	Total
Natural gas-based LPG	3.01	3.75	2.63	4.42	0.29	14.10

4. Methanol

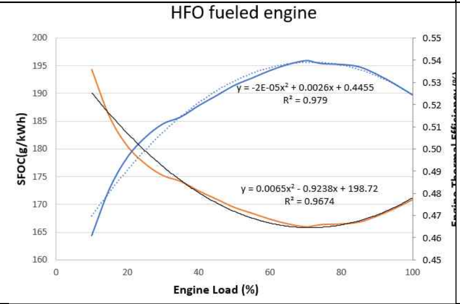
Table B-25 WtT GHG emissions (gCO_2eq./MJ) for methanol (Ellis and Svanberg, 2018, Kajaste et al., 2018, Wang et al., 2021)

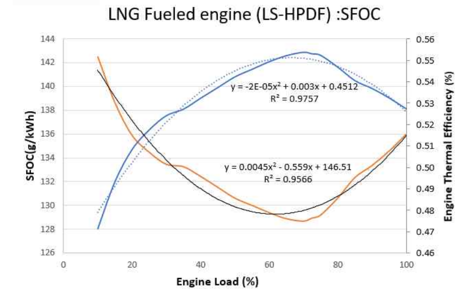
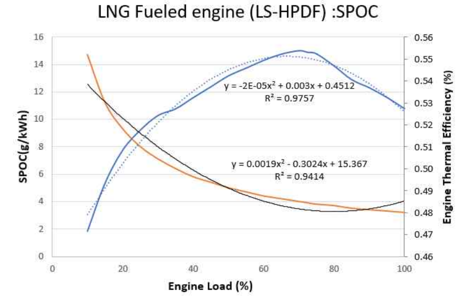
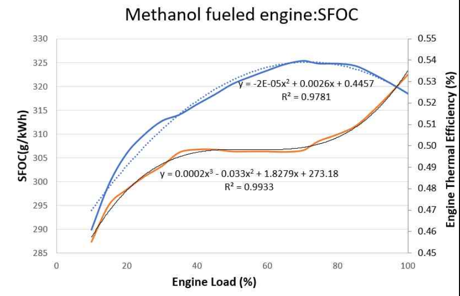
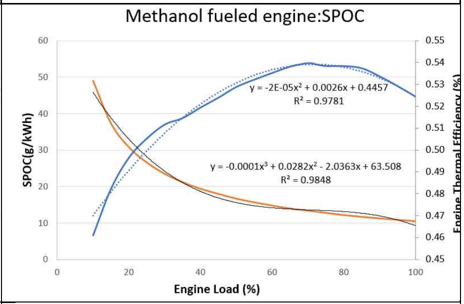
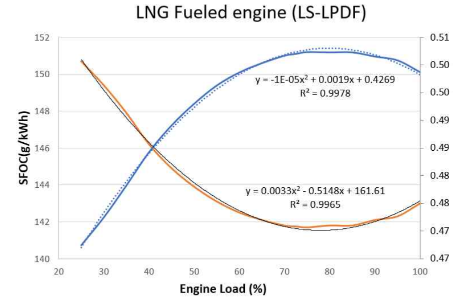
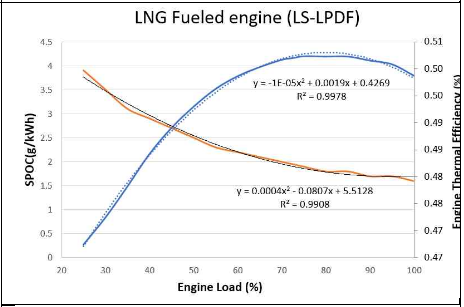
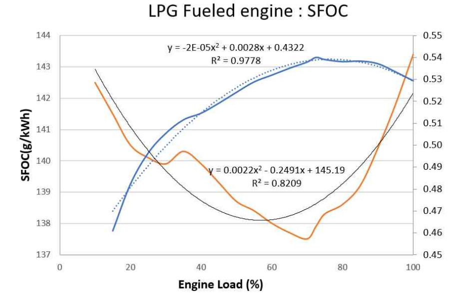
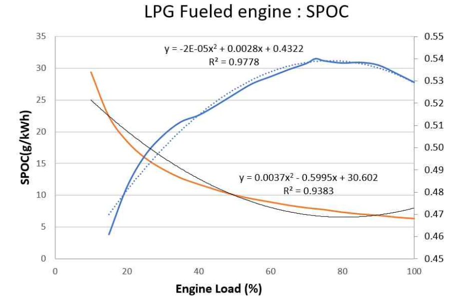
Producing countries	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ	GHG (g CO_2 eq./MJ)
Sweden	18.25	0.001002	0.00265	18.98
Sweden	20.5	0.011	0.00031	20.91
USA	18	0.14	0.00031	22.28

Section 3.2.2 (Tank-to-Wake Inventory Analysis)

1. TtW GHG emissions

Table B-26 Specific fuel oil consumption data (g/kWh) and engine efficiency depending on engine load (Section 2.2.2.4 Fuel consumption estimation model) : The orange graph shows specific fuel oil consumption data (g/kWh), and the blue line shows engine efficiency.

Engine Type	Main fuel(SFOC)	Pilot fuel(SPOC)
HFO : Low-speed diesel cycle engines (LSD)		-

LNG : Low-speed high-pressure dual-fuel engines (LS-HPDF)		
Methanol : Low-speed diesel cycle engines (LSD)		
Low-speed low-pressure dual-fuel engines ㅊ		
Low-speed diesel cycle engines (LSD)		

Based on the specific fuel consumption corresponding to the engine load provided by MAN CEAS Engine Calculations and WinGD General Technical Data, engine thermal efficiency is estimated with following equation.

$$\text{Engine efficiency} = \frac{Work\ out}{Heat\ in} = \frac{\text{Power at specific engine load (KW)}}{(\text{SFOC} + \text{SPOC}) \times \text{LCV} \times \frac{1}{3.6}}$$

where; SFOC: Specific fuel consumption (g/kWh) for primary fuel at specific engine load, SPOC: Specific fuel consumption (g/kWh) for pilot fuel at specific engine load, LHV : Lower heating value of fuel (kJ/kg)

Table B-27 Transport GHG emissions per transport work depending on the applied propulsion system based on ship’s operation data

Cargo capacity & propulsion system	t CO_2 eq	t LNG carried	mile	t CO_2 eq / mile	t CO_2 eq /t LNG carried	g CO_2 eq / mile & t LNG carried
125K LNG Carrier (Steam turbine)	5087.2	52541.9	4819.6	1.06	0.10	20.09
	5050.3	52484.5	4800.0	1.05	0.10	20.05
	6225.3	52497.7	5757.6	1.08	0.12	20.60
	5516.6	52379.1	5166.5	1.07	0.11	20.39
	5877.0	52596.7	5141.0	1.14	0.11	21.73
	4784.4	52686.4	4785.5	1.00	0.09	18.98
	4709.6	52652.8	4938.9	0.95	0.09	18.11
	5197.3	52559.8	5073.1	1.02	0.10	19.49
	7773.9	52859.0	5209.1	1.49	0.15	28.23
	8406.7	52561.5	5587.2	1.50	0.16	28.63
	5036.7	52610.3	4752.2	1.06	0.10	20.15
	7834.2	52363.4	5338.0	1.47	0.15	28.03
	5284.1	52543.6	4962.8	1.06	0.10	20.26
	5914.6	52390.6	5088.7	1.16	0.11	22.19
	5102.7	52626.5	4968.0	1.03	0.10	19.52
	5871.6	49958.3	5434.8	1.08	0.12	21.63
	5815.4	52484.5	4986.5	1.17	0.11	22.22
	5546.5	52484.5	4499.6	1.23	0.11	23.49
	5609.1	52881.5	5152.0	1.09	0.11	20.59
	5863.3	52340.5	5395.7	1.09	0.11	20.76
	5793.1	52251.6	5143.5	1.13	0.11	21.56
	5800.0	52321.3	5362.6	1.08	0.11	20.67
	9320.0	52506.2	5263.1	1.77	0.18	33.73
	5998.8	52519.4	5267.2	1.14	0.11	21.69
	6615.4	52638.0	4810.7	1.38	0.13	26.12
	5411.3	52634.1	4945.9	1.09	0.10	20.79
	6176.7	49950.7	5588.9	1.11	0.12	22.13
	6474.6	52265.2	5322.8	1.22	0.12	23.27
	5615.6	53309.5	5221.7	1.08	0.11	20.17
	10350.7	51499.0	9624.0	1.08	0.20	20.88
	11926.1	50849.6	11337.0	1.05	0.23	20.69
	10311.9	50803.8	9540.0	1.08	0.20	21.28
	9809.1	50824.8	8756.0	1.12	0.19	22.04
	9963.0	50786.9	8949.0	1.11	0.20	21.92
	10367.4	51744.7	9428.0	1.10	0.20	21.25
	10489.8	51738.0	9623.0	1.09	0.20	21.07
	10459.6	51719.9	9613.0	1.09	0.20	21.04
	9966.8	51742.6	9075.0	1.10	0.19	21.23
	11122.9	51729.1	10298.0	1.08	0.22	20.88
	10675.7	51780.1	10012.0	1.07	0.21	20.59
	10319.7	51508.0	9301.0	1.11	0.20	21.54
	10082.1	51498.0	9468.0	1.06	0.20	20.68
	9822.4	51515.0	9051.0	1.09	0.19	21.07
	16192.6	54289.5	12447.0	1.30	0.30	23.96
	15570.5	54667.3	11773.0	1.32	0.28	24.19

135K LNG Carrier (Steam turbine)	17032.9	63223.0	13125.0	1.30	0.27	20.53
	16029.4	63146.0	12144.0	1.32	0.25	20.90
	15847.9	62038.0	12070.0	1.31	0.26	21.16
	17254.4	62009.0	11807.0	1.46	0.28	23.57
	16591.1	60649.0	11806.0	1.41	0.27	23.17
	16718.1	59978.0	11917.0	1.40	0.28	23.39
	16320.3	56254.7	11946.0	1.37	0.29	24.29
	18548.0	53998.8	13285.0	1.40	0.34	25.86
	17513.7	62277.0	13132.0	1.33	0.28	21.42
	17275.6	62193.0	13210.0	1.31	0.28	21.03
	16323.8	60672.0	12932.0	1.26	0.27	20.80
	15891.2	60428.0	12964.0	1.23	0.26	20.29
	17123.4	59376.0	13488.0	1.27	0.29	21.38
	17072.0	60552.0	12840.0	1.33	0.28	21.96
	16535.0	60517.0	12712.0	1.30	0.27	21.49
	16784.9	60657.0	12912.0	1.30	0.28	21.43
	15514.0	60234.0	13132.0	1.18	0.26	19.61
	18735.6	60133.0	13203.0	1.42	0.31	23.60
	19018.3	62318.0	12872.0	1.48	0.31	23.71
	19070.6	60077.0	12782.0	1.49	0.32	24.83
	19504.3	60029.0	12761.0	1.53	0.32	25.46
	17224.5	60050.0	12797.0	1.35	0.29	22.41
	17401.1	60090.0	13034.0	1.34	0.29	22.22
	19584.8	60078.0	13302.0	1.47	0.33	24.51
	19523.6	60074.0	13298.0	1.47	0.32	24.44
	17971.0	60559.0	12847.0	1.40	0.30	23.10
	17161.6	60559.0	12791.0	1.34	0.28	22.16
	17579.9	60577.0	13143.0	1.34	0.29	22.08
	17336.4	59317.0	12877.0	1.35	0.29	22.70
	16724.6	54516.5	13134.0	1.27	0.31	23.36
174K LNG Carrier(LS-HPDP)	21126.9	68618.8	21429.8	0.99	0.31	14.37
	15847.4	68924.0	20327.0	0.78	0.23	11.31
	16946.4	68935.0	20372.0	0.83	0.25	12.07
	18576.5	71309.1	21275.0	0.87	0.26	12.24
	18109.3	71420.0	21651.0	0.84	0.25	11.71
	12704.3	69582.7	20445.0	0.62	0.18	8.93
	17480.4	69293.7	20626.0	0.85	0.25	12.23
	16623.0	69704.3	21619.0	0.77	0.24	11.03
	20031.8	68648.6	22270.0	0.90	0.29	13.10
	17773.5	69300.5	21555.0	0.82	0.26	11.90
	17429.1	68892.5	20419.0	0.85	0.25	12.39
	16197.8	71205.1	19405.0	0.83	0.23	11.72

2. WtW GHG emissions

Table B-28 WtT GHG emissions (gCO$_2$eq./MJ) for marine fuels imported to South Korea

Fuel types	Geographical area	WtT emission	Energy converter	TtW emission	WtW emission	Emission Level%
HFO	Saudi Arabia	7.31	HFO fueled main engine + aux. engine	79.34	86.65	87.63%
HFO	Kuwait	9.34	HFO fueled main engine + aux. engine	79.34	88.68	89.68%
HFO	Iraq	16.20	HFO fueled main engine + aux. engine	79.34	95.54	96.62%
HFO	UAE	9.72	HFO fueled main engine + aux. engine	79.34	89.06	90.07%
HFO	USA	15.08	HFO fueled main engine + aux. engine	79.34	94.42	95.49%
HFO	Mexico	13.66	HFO fueled main engine + aux. engine	79.34	93.00	94.05%
HFO	Iran	19.54	HFO fueled main engine + aux. engine	79.34	98.88	100.00%
LNG	Malaysia	18.56	LNG: LS-HPDF + MS-LPDF	58.80	77.35	78.23%
LNG	Indonesia	20.85	LNG: LS-HPDF + MS-LPDF	58.80	79.65	80.55%
LNG	Australia	15.46	LNG: LS-HPDF + MS-LPDF	58.80	74.25	75.10%
LNG	Qatar	17.94	LNG: LS-HPDF + MS-LPDF	58.80	76.74	77.61%
LNG	Oman	17.56	LNG: LS-HPDF + MS-LPDF	58.80	76.36	77.23%
LNG	USA	21.01	LNG: LS-HPDF + MS-LPDF	58.80	79.80	80.71%
LNG	Malaysia	18.56	LNG: LS-LPDF + MS-LPDF	66.84	85.40	86.37%
LNG	Indonesia	20.85	LNG: LS-LPDF + MS-LPDF	66.84	87.69	88.69%
LNG	Australia	15.46	LNG: LS-LPDF + MS-LPDF	66.84	82.30	83.23%
LNG	Qatar	17.94	LNG: LS-LPDF + MS-LPDF	66.84	84.79	85.75%
LNG	Oman	17.56	LNG: LS-LPDF + MS-LPDF	66.84	84.41	85.36%
LNG	USA	21.01	LNG: LS-LPDF + MS-LPDF	66.84	87.85	88.85%
LPG	Korea: Crude oil - based LPG	12.23	LPG fueled main engine + aux. engine	61.61	73.84	74.68%
LPG	USA: Natural gas-based LPG	14.10	LPG fueled main engine + aux. engine	61.61	75.71	76.57%
Methanol	Sweden	18.98	Methanol fueled main engine + aux. engine	63.93	82.90	83.84%

Methanol	Sweden	20.91	Methanol fueled main engine + aux. engine	63.93	84.84	85.80%
Methanol	USA	22.28	Methanol fueled main engine + aux. engine	63.93	86.21	87.19%

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C. Appendix : Supplementary material for: 7. A Prospective LCA Framework for Sustainable Renewable Fuels in International Shipping : Hydrogen based e fuels

1. Conventional fuel production pathways

Table C-1. Fuel production pathways and their GHG emissions

Fuel type	**Feedstock type**	**Technologies for feedstock production**	**Conversion Process type for fuel production**	**GHG emission ($gCO_2eq./MJ$)**
HFO [1]	Crude oil	Standard crude oil production	Standard refinery process	11.15
Hydrogen [2]	Natural gas	Standard NG production	Steam methane reforming and liquefaction	136.4
	Crude oil	Standard crude oil production	Naphtha cracking processes and liquefaction	44.06
Ammonia [3]	Natural gas	Standard NG production	Steam methane reforming and Haber Bosch process	160.16
LNG [1]	Natural gas	Standard NG extraction	Standard LNG production including liquefaction	18.14
Methanol [1]	Natural gas	Standard NG production	Steam methane reforming and methanol synthesis	31.26

[1] The GHG emission values were adopted from our previous study (Ha et al., 2023),

[2] In this study, referring to Table C-2, a weighted average value of 97.62 $gCO_2eq./MJ$ has been adopted.

[3] The GREET model, as described by (Wang et al., 2021), was adopted. Additionally, maritime transportation data indicating 8.43 g CO_2 eq./MJ for an ammonia carrier were incorporated from (JTTRI, 2022).

Table C-2. Hydrogen production and sales in South Korea (Korea Energy Agency, 2018, Choi et al., 2020)

Technologies	Percentage (%)	Weighted percentage in this study (%)
Naphtha cracking	34	42
Steam methane reforming(SMR)	47	58
Others	19	-

2. Hydrogen based e fuels : hydrogen

Table C-3. Hydrogen production by water electrolysis (Liu et al., 2020a, Wang et al., 2021)

Technologies	Electricity (GJ / t $_{H2}$)	Efficiency (%)	kWh /kg $_{H2}$
PEM electrolysis	190	63	52.78

Alkaline electrolysis	172	70	47.77

Table C-4. Hydrogen liquefaction (Yin and Ju, 2020)

	kWh /kg $_{H2}$
Liquefaction	6.5

The specific energy consumption (SEC) of current liquefaction plants falls within the range of 11 to 15 kWh/kgLH2 (Stolzenburg et al., 2013). This accounts for 33 to 45 percent of the energy content of hydrogen, as determined by its lower heating value. A review of various studies on SEC for liquefaction plants is presented by (Yin and Ju, 2020) who found that existing designs maintain an SEC in the range of 5 to 8 kWh/kgH2, closely aligning with the findings of (Eckroll, 2017). For this study, a moderate SEC of 6.5 kWh/kgLH2 is assumed.

Table C-5. Maritime transportation of hydrogen (JTTRI, 2022)

	GHG emission (gCO_2eq./MJ)
Maritime transportation	4.6

3. Hydrogen based e fuels : LNG (Methane)

Table C-6. Assumption on mass flow for methane production[1] (Naohiro Murata, 2021)

Methane LHV(MJ/kg)	49.2
Electricity Grid (kg CO_2 eq/kWh)	0.56
Methanation (kg/h)	6808.1
CO_2 handled (kg/h)	18970.4
Hydrogen (kg/h)	3432.3
CO_2 emission factor for steam generation (t-CO_2 eq/GJ)	0.06

[1] The Sabatier reaction is a method for thermochemical methanation, represented by the equation: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$). It is assumed that the annual production of methane is 54,458 tons/year and that of CO_2 is 150,000 tons/year.

Table C-7. Hydrogen for methane production (Liu et al., 2020a, Wang et al., 2021)

Technologies	Electricity (GJ / ton $_{H2}$)	kWh /kg $_{H2}$	kWh / kg $_{CH4}$
PEM electrolysis	190	52.78	26.61
Alkaline electrolysis	172	47.77	24.08

CO_2 capture from industrial point sources (From Table C-8 to Table C-13)

Table C-8. CO_2 capture from industrial point sources - Chemical(Amine) absorption method (Naohiro Murata, 2021)

Process	Required steam energy for CO_2 recovery (GJ/t $_{CO2}$)	kWh/ kg $_{CO2}$	kWh/kg $_{CH4}$
Chemical absorption method [1]	2.88[1]	0.80	2.23

[1] In this study, the reboiler energy efficiency of 80% was considered when calculating the steam energy required for recovering CO_2 from the amine absorption solution with CO_2 recovery energy. 22% of the CO_2 concentration in the blast furnace gas is assumed. This study assumes that the required steam energy is generated using electricity; therefore, the electricity input is considered instead of the heat input (Kanchiralla et al., 2022).

Table C-9. CO_2 capture from industrial point sources - Chemical(Amine) absorption method (liquefaction etc) (Naohiro Murata, 2021)

Process	Required electricity(kWh)	kWh/kg $_{CO2}$	kWh/kg $_{CH4}$
CO_2 liquefaction	15,600,000	0.10	0.29
CO_2 storage	1,220,000	0.01	0.02
CO_2 transport (pump)	75,000	0.0005	0.0014

Based on our assumed annual transport amount of 150,000 t, we specified the CO_2 production amount as 18 t/h, and the raw material gas supply volume as approximately 64,000 m3 /h.

Table C-10. CO_2 production - Physical adsorption method: Pressure Swing Adsorption (PSA) (1/2) (Naohiro Murata, 2021)

Process	CO_2 regeneration energy (KJ/t $_{CO2}$)	kWh/ kg $_{CO2}$	kWh/kg $_{CH4}$
Regeneration at the dehumidifier	42	0.01	0.03

Table C-11. CO_2 production - Physical adsorption method : Pressure Swing Adsorption (PSA) (2/2) (Naohiro Murata, 2021)

Process	Required electricity (MWh)
Blower, vacuum pump, liquefaction equipment	64,500

Table C-12. CO_2 transport by maritime transportation (Naohiro Murata, 2021)

Cargo capacity(M3)	GHG emission ($tCO_2eq.$)	GHG emission ($tCO_2eq./t_{CO2}$)	GHG emission ($tCO_2eq./t_{CH4}$)
10000	20500	0.14	0.38

Table C-13. CO_2 vaporisation (Naohiro Murata, 2021)

Process	Required electricity(MWh)
CO_2 tank	1,489
Evaporator	16,667

<u>CO_2 capture from air : Direct air capture (DAC)</u>

Table C-14. Energy demand of DAC technologies in this study. (Deutz and Bardow, 2021).

Technology	Electricity (kWh/kg_{CO2})	Thermal energy (MJ/kg_{CO2})
DAC	0.7	4.7

Based on data from Climeworks' experience, this study estimates that the electricity and thermal energy demand is 0.7 kWh/kg_{CO2} and 4.7 MJ/kg_{CO2} captured, respectively. A heat pump system with a Coefficient of Performance (COP) of 2.51, operating on grid electricity, is assumed to deliver the thermal energy (Deutz and Bardow, 2021).

Table C-15. Methanation process (Naohiro Murata, 2021)

Process	Required electricity (MWh)
Methanation reactor	2,042

Table C-16. Methanation liquefaction (Naohiro Murata, 2021)

Process	Required electricity(MWh) from Grid	Electricity(MWh) from Gas turbine
liquefaction	21,200[1]	
	-	14,400[1]

[1] In this study, when calculating GHG emissions from the liquefaction process, it is assumed that the total required electricity is 35,600 (21,200 + 14,400) MWh, generated from the grid.

Table C-17. Maritime transport emissions based on ship's Abstract LOG data from Korean shipping companies (Ha et al., 2023)

	Voyages	Ave. miles	Cargo carried (t)	Cargo capacity (Steam turbine)	GHG emissions (t CO_2eq)	gCO_2eq./ MJ	gCO_2 eq./t & mile
Australia	14	9577	719,739	125K	145667	4.11	1.51

4. Hydrogen based e fuels : Ammonia

Table C-18. Mass balance for ammonia production[1] per metric ton NH_3

Component	Mass per ton NH3
N_2 at 8bar	0.822
H_2 at 20bar	0.178

[1] The Haber-Bosch process is described by the equation: $N_2 + 3H_2 \rightarrow 2NH_3$. In this method, hydrogen and nitrogen combine in a 3:1 ratio in an exothermic process.

Table C-19. Hydrogen production (Liu et al., 2020a, Wang et al., 2021)

Technologies	Electricity (GJ / ton $_{H2}$)	Efficiency	kWh /kg $_{H2}$	kWh /kg $_{NH3}$
PEM electrolysis	190	63	52.78	9.39
Alkaline electrolysis	172	70	47.77	8.50

Table C-20. N_2 production (Liu et al., 2020a, Belloni, 2008)

Technologies	Electricity (GJ / ton $_{N2}$)	kWh /kg $_{N2}$
Cryogenic distillation	0.58	0.16
Pressure swing adsorption(PSA)	1.31	0.36

Table C-21. Ammonia production (Liu et al., 2020a)

Technologies	Electricity (GJ / ton $_{NH3}$)	kWh / kg $_{NH3}$
Electric-based Haber-Bosch	1.17	0.32

Table C-22. Maritime transport emissions based on ship's Abstract LOG data from Korean shipping companies (Ha et al., 2023)

	Ave. miles	Cargo capacity (Propulsions system)	gCO_2-eq/MJ

Australia	10,000	83K (Diesel Engine)	3.95
USA	21336.6	83K (Diesel Engine)	8.43

5. Hydrogen based e fuels : Methanol

Table C-23. Mass balance for methanol production [1] (Adnan and Kibria, 2020)

Methanol LHV(MJ/kg)	20.1
Electricity Grid (kg CO_2 eq/kWh)	0.37
H2(kg/h)	8628.8
CO_2(kg/h)	62,777
MeOH(kg/h)	44,065
CO_2 emission factor for steam generation (t-CO_2 eq/GJ)	0.06

[1] The synthesis of methanol in the reactor can be described by the equation: $CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

Table C-24. Hydrogen for methane production (Liu et al., 2020a, Wang et al., 2021, Adnan and Kibria, 2020)

Technologies	Electricity (GJ / ton $_{\text{H2}}$)	kWh /kg $_{\text{H2}}$	kWh / kg $_{\text{MeOH}}$
PEM electrolysis	190	52.78	10.34
Alkaline electrolysis	172	47.77	9.35

<u>CO_2 capture from industrial point source (Fossil)</u>

Table C-25. CO_2 capture for methane production – Chemical(Amine) absorption method (1/2) (Naohiro Murata, 2021)

Process	Required steam energy for CO_2 recovery (GJ/t $_{\text{CO2}}$)	kWh/ kg $_{\text{CO2}}$	kWh/kg $_{\text{MeOH}}$
Chemical absorption method [1]	2.88[1]	0.80	1.14

[1] In this study, the reboiler energy efficiency of 80% was considered when calculating the steam energy required for recovering CO_2 from the amine absorption solution with CO_2 recovery energy.

Table C-26. CO_2 capture for methane production – Chemical(Amine) absorption method (liquefaction etc) (2/2) (Naohiro Murata, 2021)

Process	Required electricity(kWh)	kWh/kg $_{\text{CO2}}$	kWh/kg $_{\text{MeOH}}$

CO_2 liquefaction	15,600,000	0.10	0.15
CO_2 storage	1,220,000	0.01	0.01
CO_2 transport (pump)	75,000	0.001	0.001

Table C-27. CO_2 production - Physical adsorption method (PSA) (1/2) (Naohiro Murata, 2021)

Process	CO_2 Regeneration energy (KJ/t $_{CO2}$)	kWh/ kg $_{CO2}$	kWh/kg $_{MeOH}$
Regeneration at the dehumidifier	42	0.01	0.02

Based on our assumed annual transport amount of 150,000 t, we specified the CO_2 production amount as 18 t/h, and the raw material gas supply volume as approximately 64,000 m3 /h.

Table C-28. CO_2 production - Physical adsorption method (PSA) (2/2) (Naohiro Murata, 2021)

Process	Required electricity(MWh)	kWh/ kg $_{CO2}$	kWh/kg $_{MeOH}$
Blower, vacuum pump , liquefaction equipment	64,500	0.43	0.61

CO_2 capture from air : Direct air capture (DAC)

Table C-29. Energy demand of DAC technologies in this study. (Deutz and Bardow, 2021)

Technology	Electricity (kWh/kg$_{CO2}$)	Thermal energy (MJ/kg$_{CO2}$)
Solid sorbent DAC	0.7	4.7

Table C-30. CO_2 transport by ship

Cargo capacity (M^3)	GHG emission ($tCO_2eq.$)	GHG emission ($tCO_2eq./t_{MeOH}$)	GHG emission ($gCO_2eq./MJ_{MeOH}$)
10,000	20,500	0.19	9.69

Table C-31. Methanol synthesis

Process	Required electricity (kWh / kg $_{MeOH}$)
Methanol synthesis and purification	0.33

Using ASPEN modelling from the literature (Adnan and Kibria, 2020), the energy requirements for methanol synthesis and purification were estimated as an electricity consumption of 0.33 kWh/kg $_{MeOH}$ (Meunier et al., 2020).

Table C-32. Maritime transport emissions (55K Methanol carrier) based on fuel consumption data from a shipbuilder (Ha et al., 2023)

Producing countries	Voyage miles	Cargo carried(ton)	GHG emissions (t CO_2eq)	GHG emissions (gCO_2 eq./MJ)
USA	21336	40703.87	5094.75	6.29
Australia	9576.79	40703.87	2286.81	2.82

6. Distribution in WtT part

Table C-33. GHG emissions during the distribution stage for fuel (gCO_2 eq./MJ)

	Base(2022)	2030	2040	2050
Hydrogen	0.49	0.34	0.17	0.00
Methane	0.49	0.34	0.17	0.00
Methanol	0.11	0.08	0.04	0.00
Ammonia	0.16	0.11	0.05	0.00

Section 7.2.2 Electricity production scenarios: grid's mixed electricity, and off-grid from renewable energy sources

1. Carbon intensity on grid's mixed electricity

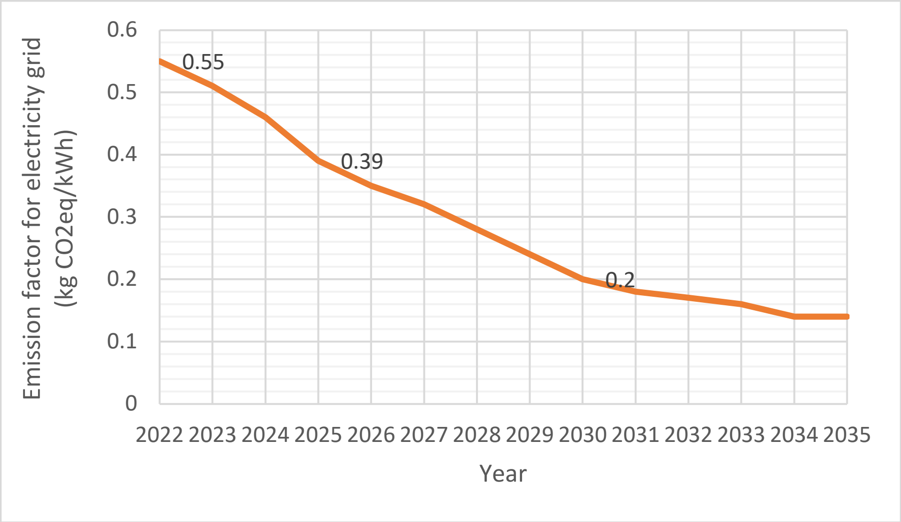

Figure C-1. Australia's National Electricity Market (NEM) Forecast (Department of Climate Change, 2022, Donald et al., 2023)

In 2022, the emission factor for Australia's electricity grid is 0.56 kg CO_2eq/kWh. With the proportion of renewable electricity expected to increase, the carbon intensity is expected to lower to 0.14 by 2034.

2. Carbon intensity on off-grid from renewable energy sources

Table C-34. Carbon intensity with renewable energy sources : PV and wind farm

Technologies	Electricity[1] (gCO_2eq./kWh)	Reference
Photovoltaic (PV)	6.15	(Marashli et al., 2022)
Wind farm	0.49 - 0.74	(Hatch, 2014, Mallia and Lewis, 2013).

[1] The system boundary was limited to the operational stage, excluding production, construction, and material disposal

Section 7.2.3 Energy efficiency improvement through energy-saving technologies

In evaluating the efficiency of propulsion-related technologies, it is imperative to consider their CO_2 abatement potential from a compounded perspective. Specifically, for the technologies listed in Groups 1 to 6, simply adding up their individual CO_2 emission reductions would offer an oversimplified, and potentially misleading, view of their collective effectiveness. Instead, a more accurate assessment necessitates taking into account their compounded effects. This method underscores the interdependent and multiplicative impact of these technologies in achieving CO_2 emission reductions. Therefore, it is crucial to assess their collective impact based on the product of their individual CO_2 abatement potentials, rather than the sum.

The following methodology is applied for compounded CO_2 abatement potential:

Firstly, the initial CO_2 emissions (E_0) are established, followed by the definition of the abatement potential for each technology, denoted as $r_{\_i}$, representing the reduction potential (αj %) of the ith technology.

Subsequently, the remaining emissions after the application of each technology are calculated sequentially:

- $E_{\_n} = E_{\_n-1} \times (1 - r_{\_n})$

This is done by reducing the previous emissions total by the respective abatement potential. Ultimately, the total amount of CO_2 emissions reduced (ΔE) after the implementation of all technologies is determined by:

- $\Delta E = E_0 - E_{\_n}$

This methodology ensures that the reduction potential of each technology is applied to the remaining CO_2 emissions, thereby accounting for the compounding effect.

Table C-35. Selected energy saving technologies and their CO_2 reduction potential (αj %) compared to base year (IMO, 2020)

Group	Selected technologies	2030	2040	2050
1	Propeller maintenance	2.20%	3.08%	3.95%
2	Hull maintenance	2.22%	3.06%	3.90%
3	Optimization water flow hull openings	1.64%	2.32%	3%

4	Hull coating	1.48%	2.02%	2.55%
5	Propeller improvements	1.40%	1.90%	2.40%
6	Air lubrication	1.35%	1.81%	2.26%
7	Steam plant improvements	1.30%	1.72%	2.13%
8	Main engine improvements	0.25%	0.35%	0.45%
9	Reduced auxiliary power usage	0.40%	0.56%	0.71%
10	Auxiliary systems	0.87%	1.23%	1.59%
11	Wind power	0.89%	1.28%	1.66%
12	Super light ship	0.28%	0.34%	0.39%
13	Waste heat recovery	1.68%	2.39%	3.09%
14	Solar panels	0.18%	0.24%	0.30%

Given that CO_2 emissions constitute the majority of total GHG emissions, the CO_2 reduction rate (αj%) from the above table was applied to calculate the annual GHG emissions for the entire fleet using the same reduction rate (αj%). Further details, including the total GHG emission reduction (ΔE) achieved using energy-saving technologies, can be found in the table above.

Section 7.3.1 Comparison of WtT GHG emissions from fossil based fuels and hydrogen based e fuels :

The following tables present estimated GHG emissions for each Well-to-Tank (WtT) phase, depending on the electricity energy source (grid, wind farm, and photovoltaic), for projected future years: the base year, 2030, 2040, and 2050.

1. Hydrogen

Table C-36. GHG emission ($gCO_2eq./MJ_{H2}$) from water electrolysis

	Grid				Wind farm				Photovoltaic			
Technologies	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
PEM electrolysis	246.31	84.18	55.56	30.03	0.27	0.17	0.08	0.00	2.70	1.73	0.81	0.00
Alkaline electrolysis	222.93	77.16	51.85	28.13	0.25	0.16	0.08	0.00	2.45	1.58	0.76	0.00

Table C-37. GHG emission ($gCO_2eq./MJ_{H2}$) from hydrogen liquefaction

	Grid				Wind farm				Photovoltaic			
Technologies	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
Hydrogen liquefaction	30.33	10.83	7.58	4.33	0.03	0.02	0.01	0.00	0.33	0.22	0.11	0.00

Table C-38. GHG emission ($gCO_2eq./MJ_{H2}$) from hydrogen liquid carrier

	Grid				Wind farm				Photovoltaic			
	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
Hydrogen Liquid carrier	4.60	3.93	1.75	0.92	4.60	3.93	1.75	0.92	4.6	3.93	1.75	0.92

2. LNG

Table C-39. GHG emission ($gCO_2eq./MJ_{CH4}$) from water electrolysis

	Grid				Wind farm				Photovoltaic			
Technologies	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
PEM electrolysis	302.87	103.50	68.31	36.93	0.34	0.21	0.10	0.00	3.33	2.12	1.00	0.00
Alkaline electrolysis	274.12	94.88	63.76	34.59	0.30	0.19	0.10	0.00	3.01	1.95	0.93	0.00

Table C-40. GHG emission ($gCO_2eq./MJ_{CH4}$) from CO_2 production: Chemical(Amine) absorption method (1/2)

	Grid				Wind farm				Photovoltaic			
Technologies	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
Chemical(Amine) absorption method	25.37	9.06	6.34	3.62	0.03	0.02	0.01	0.00	0.28	0.01	0.09	0.00

Table C-41. GHG emission ($gCO_2eq./MJ_{CH4}$) from CO_2 production: Chemical(Amine) absorption method (2/2)

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
CO_2 liquefaction	3.26	1.16	0.82	0.47	0.0037	0.0024	0.0012	0.0000	0.0362	0.0241	0.0121	0.0000
CO_2 storage	0.25	0.09	0.06	0.04	0.0003	0.0002	0.0001	0.0000	0.0028	0.0019	0.0009	0.0000
CO_2 transport (pump)	0.13	0.04	0.03	0.02	0.00002	0.00001	0.00001	0.00000	0.0002	0.0001	0.0001	0.0000

Table C-42. GHG emission ($gCO_2eq./MJ_{CH4}$) from CO_2 production: Pressure swing adsorption (PSA) (1/2)

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
Regeneration at the dehumidifier	0.37	0.13	0.09	0.05	0.0004	0.0003	0.0001	0.0000	0.0041	0.0027	0.0014	0.0000

Table C-43. GHG emission (gCO_2eq./MJ $_{CH4}$) from CO_2 production: Pressure swing adsorption (PSA) (2/2)

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
Blower, vacuum pump, liquefaction equipment	13.48	4.81	3.37	1.93	0.12	0.08	0.04	0.00	1.18	0.79	0.39	0.00

Table C-44. GHG emission (gCO_2eq./MJ $_{CH4}$) from liquefied CO_2 carrier

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
CO_2 Carrier	7.74	6.62	2.94	1.55	7.74	6.62	2.94	1.55	7.74	6.62	2.94	1.55

Table C-45. GHG emission (gCO_2eq./MJ $_{CH4}$) from CO_2 vaporisation

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
CO_2 tank	0.31	0.89	0.62	0.36	0.003	0.002	0.001	0.000	0.03	0.02	0.01	0.00
Evaporator	3.48	9.95	6.97	3.98	0.03	0.02	0.01	0.00	0.30	0.20	0.10	0.00

Table C-46. GHG emission (gCO_2eq./MJ $_{CH4}$) from CO_2 production: DAC

	Grid				Wind farm				Photovoltaic			
Technologies	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
Solid sorbent DAC	63.43	19.60	10.86	4.98	0.07	0.04	0.02	0.00	0.69	0.40	0.16	0.00

Table C-47. GHG emission (gCO_2eq./MJ $_{CH4}$) from methanation

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050

Methanation reactor	0.43	0.15	0.11	0.06	0.0005	0.0003	0.0002	0.0000	0.0046	0.0031	0.0015	0.0000

Table C-48. GHG emission (gCO$_2$eq./MJ $_{CH4}$) from methanation

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
Liquefaction	7.44	2.66	1.86	1.06	0.06	0.04	0.02	0.00	0.64	0.43	0.21	0.00

Table C-49. GHG emission (gCO$_2$eq./MJ $_{CH4}$) from LNG carrier

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
LNG Carrier	4.11	3.51	1.56	0.82	4.11	3.51	1.56	0.82	4.11	3.51	1.56	0.82

3. Ammonia

Table C-50. GHG emission (gCO$_2$eq./MJ $_{NH3}$) from water electrolysis

	Grid				Wind farm				Photovoltaic			
Technologies	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
PEM electrolysis	282.86	96.67	63.80	34.49	0.31	0.20	0.10	0.00	3.11	2.07	1.04	0.00
Alkaline electrolysis	256.01	88.61	59.55	32.30	0.28	0.18	0.09	0.00	2.81	1.87	0.94	0.00

Table C-51. GHG emission (gCO$_2$eq./MJ $_{NH3}$) from N$_2$ production

	Grid				Wind farm				Photovoltaic			
Technologies	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
Cryogenic distillation	4.01	1.43	1.00	0.57	0.004	0.003	0.00	0.00	0.04	0.03	0.01	0.00
Pressure swing adsorption(PSA)	9.03	3.22	2.26	1.29	0.01	0.01	0.00	0.00	0.10	0.07	0.03	0.00

Table C-52. GHG emission (gCO$_2$eq./MJ NH$_3$) from ammonia production

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
Electric-based Haber-Bosch	9.74	3.48	2.44	1.39	0.01	0.01	0.00	0.00	0.11	0.07	0.04	0.00

Table C-53. GHG emission (gCO$_2$eq./MJ $_{NH3}$) from ammonia carrier

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
Ammonia Carrier (Australia)	3.95	3.38	1.50	0.79	3.95	3.38	1.50	0.79	3.95	3.38	1.50	0.79
Ammonia Carrier (USA)	8.43	7.21	3.20	1.69	8.43	7.21	3.20	1.69	8.43	7.21	3.20	1.69

4. Methanol

Table C-54. GHG emission (gCO$_2$eq./MJ $_{MeOH}$) from water electrolysis

	Grid				Wind farm				Photovoltaic			
Technologies	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
PEM electrolysis	287.95	98.41	64.95	35.11	0.32	0.20	0.10	0.00	3.16	2.02	0.95	0.00
Alkaline electrolysis	260.62	90.21	60.62	32.89	0.29	0.18	0.09	0.00	2.86	1.85	0.89	0.00

Table C-55. GHG emission (gCO$_2$eq./MJ $_{MeOH}$) from CO$_2$ production: Chemical(Amine) absorption method (1/2)

	Grid				Wind farm				Photovoltaic			
Technologies	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
Chemical(Amine) absorption method	31.76	11.34	7.94	4.54	0.04	0.02	0.01	0.00	0.35	0.23	0.12	0.00

Table C-56. GHG emission ($gCO_2eq./MJ_{MeOH}$) from CO_2 production: Chemical(Amine) absorption method (2/2)

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
CO2 liquefaction	4.13	1.47	1.03	0.59	0.00457	0.00302	0.00155	0.00000	0.05	0.03	0.02	0.00
CO2 storage	0.32	0.12	0.08	0.05	0.00036	0.00024	0.00012	0.00000	0.004	0.002	0.001	0.000
CO2 transport (pump)	0.02	0.01	0.00	0.00	0.00002	0.00001	0.00001	0.00000	0.0002	0.0001	0.0001	0.0000

Table C-57. GHG emission ($gCO_2eq./MJ_{MeOH}$) from CO_2 production: Pressure swing adsorption (PSA) (1/2)

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
Regeneration at the dehumidifier	0.46	0.17	0.12	0.07	0.0005	0.0003	0.0002	0.0000	0.0051	0.0034	0.0017	0.0000

Table C-58. GHG emission ($gCO_2eq./MJ_{MeOH}$) from CO_2 production: Pressure swing adsorption (PSA) (2/2)

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
Blower, vacuum pump, liquefaction equipment	17.07	6.10	4.27	2.44	0.02	0.01	0.01	0.00	0.19	0.12	0.06	0.00

Table C-59. GHG emission ($gCO_2eq./MJ_{MeOH}$) from liquefied CO2 carrier

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
CO_2 Carrier	9.69	8.28	3.68	1.94	9.69	8.28	3.68	1.94	9.69	8.28	3.68	1.94

Table C-60. GHG emission (gCO$_2$eq./MJ $_{\text{MeOH}}$) from CO$_2$ vaporisation

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
CO$_2$ tank	0.39	0.14	0.10	0.06	0.0004	0.0003	0.0001	0.0000	0.004	0.003	0.001	0.000
Evaporator	4.41	1.58	1.10	0.63	0.0049	0.0032	0.0017	0.0000	0.048	0.032	0.016	0.000

Table C-61. GHG emission (gCO$_2$eq./MJ $_{\text{MeOH}}$) from CO$_2$ production: DAC

	Grid				Wind farm				Photovoltaic			
Technologies	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
Solid sorbent DAC	79.38	24.52	13.59	6.24	0.09	0.05	0.02	0.00	0.87	0.50	0.20	0.00

Table C-62. GHG emission (gCO$_2$eq./MJ $_{\text{MeOH}}$) from methanol synthesis

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
Methanol synthesis and purification	9.19	3.28	2.30	1.31	0.01	0.01	0.00	0.00	0.10	0.07	0.03	0.00

Table C-63. GHG emission (gCO$_2$eq./MJ $_{\text{NH3}}$) from methanol carrier

	Grid				Wind farm				Photovoltaic			
Process	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050	Base(2022)	2030	2040	2050
Ammonia Carrier (Australia)	6.29	5.38	2.39	1.26	6.29	5.38	2.39	1.26	6.29	5.38	2.39	1.26
Ammonia Carrier (USA)	2.82	2.41	1.07	0.56	2.82	2.41	1.07	0.56	2.82	2.41	1.07	0.56

Section 7.2.4 Step 2 Fleet modelling (TtW part)

Table C-64. Projected transport demand (SN_transport demand) with low growth scenario (OECD_RCP 2.6_G)

Ship size (Deadweight,ton)	2030	2040	2050
100000-199999	239	537	836
200000~	84	190	295

Table C-65. Projected transport demand (SN_transport demand) with high growth scenario (SSP2_RCP2.6_L)

Ship size (Deadweight, ton)	2030	2040	2050
100000-199999	502	1129	1757
200000~	177	399	620

Table C-66. Impacts on scraping rate : SN_scrapping

Ship size (Deadweight, ton)	2030	2040	2050
100000-199999	365	822	1279
200000~	129	291	452

Table C-67. Annual number of ships scrapped

Deadweight	Average DWT	Scraping rate ton	SN $_{scrapping}$
100000-199999	252386	7080266	46
200000~	154993	4073507	16

Table C-68. Impacts on speed reduction due to regulatory requirement for GHG reduction : SN_ speed reduction

	Ship size (Deadweight, ton)	Transport work (ton·mile)	SN$_{\_ speed reduction}$
EEXI (2023)	100000-199999	354613348204	33
	200000~	219529058621	12
CII (2030)	100000-199999	1696984942542	159
	200000~	1050545640251	98

The number of ships in a given year (2030, 2040, or 2050) is calculated as follows:

- $SN_{year} = SN_{base\ year} + \sum SN_{transport\ demand} + \sum SN_{speed\ reduction} + \sum SN_{scrapping}$

Where, $SN_{\text{base year}}$: the number of ships in the base year (2062 for bulk carriers), subtracting those that have been scrapped due to aging, $SN_{\text{transport demand}}$: the number of ships added to the fleet due to increased transport demand, $SN_{\text{speed reduction}}$: the number of ships added to the fleet due to speed reduction in existing fleets, $SN_{\text{scrapping}}$: the number of newly built ships replaced those scrapped due to aging.

Table C-69. Total projected number of fleet (SN_{year}) for low growth scenario (OECD_RCP 2.6_G)

	2022	**2030**	**2040**
Existing ships	2062	1567	949
New ships due to scraping (Total SN_scrapping)	0	495	1113
New ships due to transportation demand (Total SN_transport demand)	0	323	727
New ships due to ship speed (Total SN_ speed reduction)	0	302	302
Total projected number of fleet	2062	2687	3091

Table C-70. Total projected number of fleet (SN_{year}) for high growth scenario (SSP2_RCP2.6_L)

	2022	2030	2040	2050
Existing ships in base year	2062	1567	949	331
New ships due to scraping (Total SN_scrapping)	0	495	1113	1731
New ships due to transportation demand (Total SN_transport demand)	0	679	1528	2377
New ships due to ship speed (Total SN_ speed reduction)	0	302	302	302
Total projected number of fleet	2062	3043	3892	4741

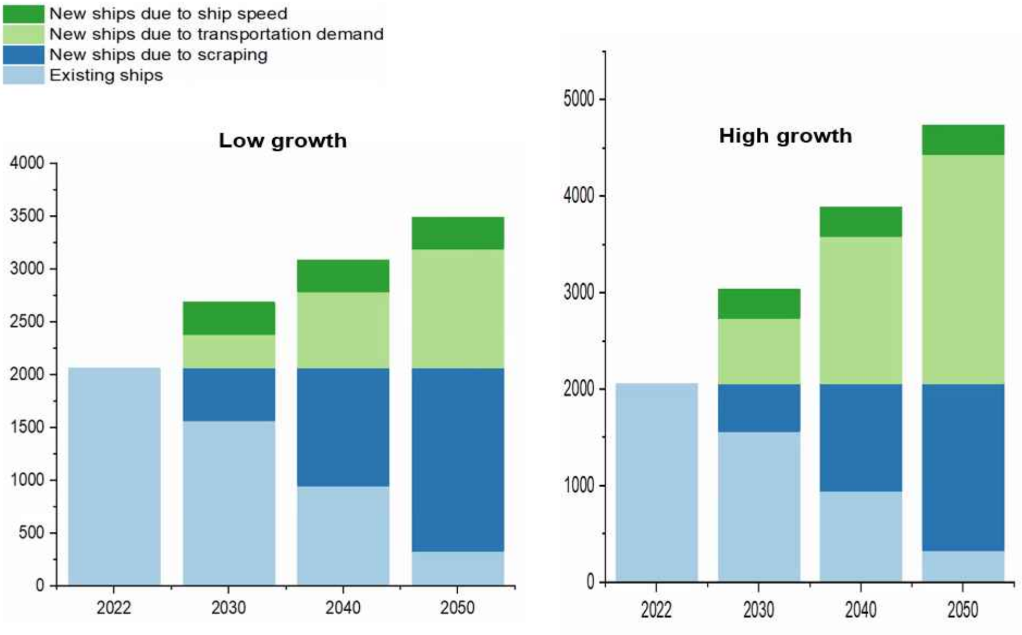

Figure C-2 Total projected number of fleet (SN_{year}) for low and high growth scenarios

Section 7.3.1 Comparison of WtT GHG emissions from fossil based fuels and hydrogen based e fuels

Table C-71. WtT GHG emission($gCO_2eq./MJ$) using off grid (Windfarm) from renewable energy sources

Fuel types	Pathway ID	Base year	2030	2040	2050
Hydrogen	PEM	5.40	4.47	2.01	0.92
	ALK	5.37	4.46	2.01	0.92
LNG	PEM_Amine	12.68	10.68	4.78	2.35
	PEM_PSA	12.76	10.72	4.80	2.84
	PEM_ DAC	5.06	4.15	1.87	0.83
	ALK_Amine	12.64	10.66	4.77	2.35
	ALK_PSA	12.73	10.85	4.79	2.35
	ALK_ DAC	5.03	4.13	2.18	1.31
	PEM_Amine	12.68	10.68	4.78	2.35
	PEM_PSA	12.76	10.72	5.12	2.84
	PEM_DAC	5.06	4.30	1.87	0.83
	ALK_Amine	12.64	10.66	4.77	2.35
	ALK_PSA	12.73	10.70	4.79	2.35
	ALK_ DAC	5.03	4.28	1.87	0.83
Ammonia	PEM_Cryo	4.43	3.69	1.66	0.95

	PEM_PSA	4.43	3.74	1.66	0.79
	ALK_Cryo	4.40	3.68	1.65	0.79
	ALK_PSA	4.41	3.73	1.65	0.79
Methanol	PEM_Amine	12.99	11.01	4.91	2.50
	PEM_PSA	12.97	11.03	4.90	2.50
	PEM_ DAC	3.35	2.75	1.30	0.67
	ALK_Amine	12.96	10.99	4.90	2.50
	ALK_PSA	12.94	10.90	4.90	2.50
	ALK_DAC	3.32	2.73	1.23	0.57

Table C-72. WtT GHG emission(gCO_2eq./MJ) using grid's mixed electricity

Fuel types	Pathway ID	Base year	2030	2040	2050
Hydrogen	PEM	281.73	99.43	65.38	35.77
	ALK	258.35	92.42	61.67	33.87
LNG	PEM_Amine	350.26	134.71	87.81	52.19
	PEM_PSA	335.34	130.66	84.98	46.49
	PEM_ DAC	372.78	145.08	92.26	49.45
	ALK_Amine	321.97	126.23	83.33	49.89
	ALK_PSA	307.05	122.18	80.49	44.19
	ALK_ DAC	344.49	136.59	87.78	47.15
	PEM_Amine	350.26	134.71	87.81	52.19
	PEM_PSA	335.34	130.66	84.98	46.49
	PEM_DAC	372.78	145.08	92.26	49.45
	ALK_Amine	321.97	126.23	83.33	49.89
	ALK_PSA	307.05	122.18	80.49	44.19
	ALK_ DAC	344.49	136.59	87.78	47.15
Ammonia	PEM_Cryo	300.72	105.11	68.90	37.40
	PEM_PSA	300.72	106.90	70.15	38.11
	ALK_Cryo	273.87	97.06	64.64	35.21
	ALK_PSA	278.88	98.85	65.89	35.93
Methanol	PEM_Amine	350.80	127.15	82.37	44.90
	PEM_PSA	332.10	120.64	77.81	42.29
	PEM_ DAC	393.95	138.74	86.91	45.96
	ALK_Amine	323.47	118.95	78.04	42.67
	ALK_PSA	304.77	112.44	73.48	40.07
	ALK_DAC	366.62	130.54	82.58	43.73

Section 7.3.2 Comparison of TtW GHG emissions from fossil based fuels and sustainable renewable fuels

Table C-73. TtW GHG emissions(CO_2 eq./MJ) based on selected fuel and technologies improvement in base year and the future (2030,2040 and 2050)

Fuel type	Carbon source	Ship Capacity (-199,999)			Ship Capacity (200,000-)		
		Main fuel	Pilot fuel	Total	Main fuel	Pilot fuel	Total
Base year							
HFO	-	79.3	-	79.3	79.3	-	79.3
Methanol	CO2_Fossil	69.3	76.1	70.0	69.3	76.1	70.0
LNG : LS-HPDF	CO2_Fossil	58.7	76.1	59.3	58.5	76.1	59.1
LNG : LS-LPDF	CO2_Fossil	66.8	76.1	66.9	66.7	76.1	66.8
Methanol	CO2_DAC	0.2	76.1	7.8	0.2	76.1	7.8
LNG : LS-HPDF	CO2_DAC	2.8	76.1	5.1	2.6	76.1	4.9
LNG : LS-LPDF	CO2_DAC	10.9	76.1	11.9	10.8	76.1	11.8
Ammonia	-	7.1	76.1	14.0	7.1	76.1	14.0
Hydrogen	-	1.0	76.1	8.5	0.9	76.1	8.4
2030							
HFO	Fossil	79.3	-	79.3	79.3	-	79.3
Methanol	CO2_Fossil	69.3	76.1	69.8	69.3	76.1	69.8
LNG : LS-HPDF	CO2_Fossil	58.3	76.1	58.7	58.1	76.1	58.6
LNG : LS-LPDF	CO2_Fossil	64.2	76.1	64.3	64.1	76.1	64.3
Methanol	CO2_DAC	0.2	76.1	5.9	0.2	76.1	5.9
LNG : LS-HPDF	CO2_DAC	2.4	76.1	4.1	2.2	76.1	4.0
LNG : LS-LPDF	CO2_DAC	8.3	76.1	9.1	8.2	76.1	9.0
Ammonia	-	5.3	76.1	10.7	5.3	76.1	10.7
Hydrogen	-	1.0	76.1	6.6	0.9	76.1	6.5
2040							
HFO	Fossil	79.3	-	79.3	0.0	-	79.3
Methanol	CO2_Fossil	69.3	76.1	69.7	69.3	76.1	69.7
LNG : LS-HPDF	CO2_Fossil	57.9	76.1	58.2	57.8	76.1	58.1
LNG : LS-LPDF	CO2_Fossil	61.7	76.1	61.8	61.6	76.1	61.7
Methanol	CO2_DAC	0.2	76.1	4.0	0.2	76.1	4.0
LNG : LS-HPDF	CO2_DAC	2.0	76.1	3.1	1.9	76.1	3.0
LNG : LS-LPDF	CO2_DAC	5.8	76.1	6.3	5.7	76.1	6.3
Ammonia	-	3.6	76.1	7.2	3.6	76.1	7.2
Hydrogen	-	1.0	76.1	4.7	0.9	76.1	4.7
2050							
HFO	Fossil	79.3	-	79.3	79.3	-	79.3
Methanol	CO2_Fossil	69.3	-	69.3	69.3	-	69.3
LNG : LS-HPDF	CO2_Fossil	57.3	-	57.3	57.3	-	57.3
LNG : LS-LPDF	CO2_Fossil	58.1	-	58.1	58.1	-	58.1
Methanol	CO2_DAC	0.2	-	0.2	0.2	-	0.2
LNG : LS-HPDF	CO2_DAC	1.4	-	1.4	1.4	-	1.4
LNG : LS-LPDF	CO2_DAC	2.3	-	2.3	2.2	-	2.2
Ammonia	-	0.04	-	0.04	0.04	-	0.04
Hydrogen	-	1.0	-	1.0	0.9	-	0.9

Table C-74. Annual GHG emissions(tons) depending on selected fuels in base year and the future (2030,2040 and 2050)

Fuel Type	Carbon source	Ship Capacity (DWT : -199,999)					Ship Capacity (DWT : 200,000-)				
		Main Engine		Auxiliary Engine		Total	Main Engine		Auxiliary Engine		Total
		Main Fuel	Pilot Fuel	Main Fuel	Pilot Fuel		Main Fuel	Pilot Fuel	Main Fuel	Pilot Fuel	
Base year											
HFO	Fossil	31,008	-	1,506	-	32,515	43,885	-	1,590	-	45,475
Methanol	CO2_Fossil	25,765	3,129	1,156	148	30,199	36,464	4,428	1,221	148	42,261
LNG : LS-HPDF	CO2_Fossil	22,682	990	1,388	20	25,081	32,101	1,401	1,465	21	34,989
LNG : LS-LPDF	CO2_Fossil	28,488	495	1,388	20	30,392	40,318	701	1,465	21	42,505
Methanol	CO2_DAC	82	3,129	6	148	3,365	117	4,428	6	148	4,699
LNG : LS-HPDF	CO2_DAC	781	990	382	20	2,173	1,105	1,401	403	21	2,931
LNG : LS-LPDF	CO2_DAC	4,491	495	382	20	5,388	6,356	701	403	21	7,481
Ammonia	-	2,821	3,347	118	140	6,426	3,993	4,736	125	148	9,002
Hydrogen	-	292	3,327	103	150	3,872	414	4,708	101	150	5,373
2030											
HFO	-	31,008	-	1,506	-	32,515	43,885	-	1,590	-	45,475
Methanol	CO2_Fossil	26,558	2,363	1,183	111	30,215	37,586	3,344	1,249	111	42,290
LNG : LS-HPDF	CO2_Fossil	22,879	742	1,311	16	24,947	32,379	1,050	1,384	17	34,829
LNG : LS-LPDF	CO2_Fossil	27,735	376	1,311	16	29,437	39,252	532	1,384	17	41,184
Methanol	CO2_DAC	85	2,363	6	111	2,564	120	3,344	6	111	3,581
LNG : LS-HPDF	CO2_DAC	701	742	293	16	1,751	992	1,050	309	17	2,368
LNG : LS-LPDF	CO2_DAC	3,470	376	293	16	4,154	4,911	532	309	17	5,769
Ammonia	-	2,171	2,504	92	105	4,872	3,073	3,544	97	111	6,825
Hydrogen	-	301	2,504	105	111	3,020	425	3,544	104	111	4,184
2040											
HFO	Fossil	31,008	-	1,506	-	32,515	43,885	-	1,590	-	45,475

Methanol	CO2_Fossil	27,276	1,575	1,215	74	30,140	38,602	2,229	1,283	74	42,188
LNG : LS-HPDF	CO2_Fossil	22,986	495	1,222	11	24,714	32,532	700	1,290	11	34,533
LNG : LS-LPDF	CO2_Fossil	26,786	250	1,222	11	28,269	37,909	354	1,290	11	39,565
Methanol	CO2_DAC	87	1,575	6	74	1,742	123	2,229	6	74	2,433
LNG : LS-HPDF	CO2_DAC	627	495	200	11	1,332	887	700	211	11	1,810
LNG : LS-LPDF	CO2_DAC	2,430	250	200	11	2,891	3,438	354	211	11	4,015
Ammonia	-	1,487	1,670	63	70	3,290	2,105	2,363	66	74	4,608
Hydrogen	-	309	1,670	107	74	2,160	437	2,363	107	74	2,980
2050											
HFO	Fossil	31,008	-	1,506	-	32,515	43,885	-	1,590	-	45,475
Methanol	CO2_Fossil	28,712	0	1,279	0	29,990	40,634	0	1,350	0	41,984
LNG : LS-HPDF	CO2_Fossil	23,247	0	1,099	0	24,346	32,900	0	1,160	0	34,060
LNG : LS-LPDF	CO2_Fossil	25,502	0	1,099	0	26,601	36,092	0	1,160	0	37,252
Methanol	CO2_DAC	92	0	6	0	98	130	0	7	0	136
LNG : LS-HPDF	CO2_DAC	524	0	70	0	593	741	0	73	0	815
LNG : LS-LPDF	CO2_DAC	961	0	70	0	1,031	1,360	0	73	0	1,434
Ammonia	-	17	0	1	0	19	25	0	1	0	26
Hydrogen	-	325	0	113	0	438	460	0	112	0	572

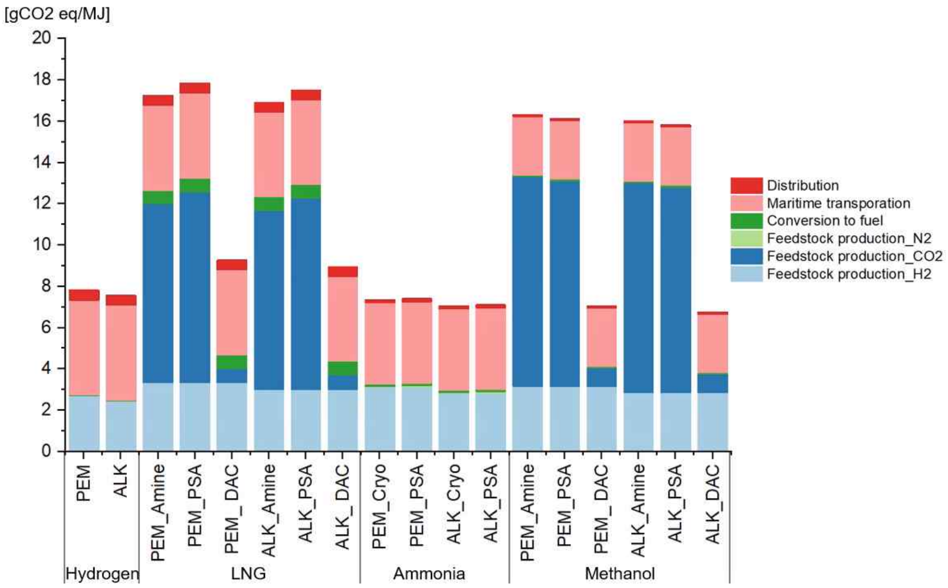

Figure C-3 WtT emissions based on selected fuel production pathway using solar power in base year (2022)

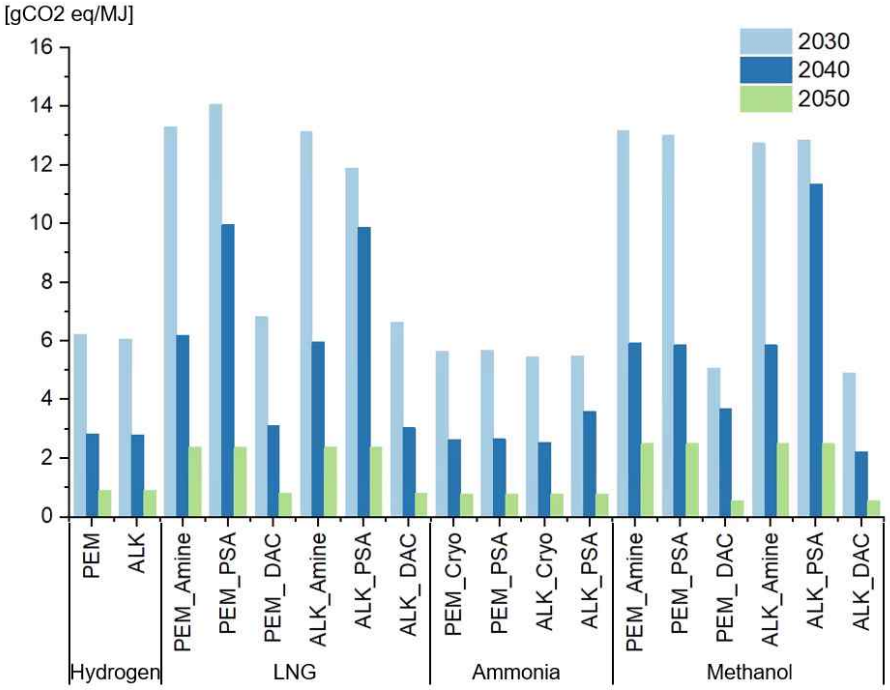

Figure C-4 WtT emissions based on selected fuel production pathway using solar power in the future(2030, 2040 and 2050)

Section 7.3.3 Comparison of WtW GHG emissions

Table C-75. WtW GHG emissions(CO_2 eq./MJ) based on selected fuel and technologies using the grid's mixed electricity in the base year

Fuel Type	H_2	CO_2 and N_2	Conversion Process	Main propulsion system	WtW emission
Methanol	PEM	Amine(PSF)	Methanol synthesis	LSD	420.8
LNG	PEM	Amine(PSF)	Methanation and liquefaction	LS-LPDF	417.2
LNG	PEM	Amine(PSF)	Methanation and liquefaction	LS-HPDF	409.5
LNG	PEM	PSA(PSF)	Methanation and liquefaction	LS-LPDF	402.3
Methanol	PEM	PSA(PSF)	Methanol synthesis	LSD	402.1
Methanol	PEM	DAC	Methanol synthesis	LSD	401.8
LNG	PEM	PSA(PSF)	Methanation and liquefaction	LS-HPDF	394.6
Methanol	ALK	Amine(PSF)	Methanol synthesis	LSD	393.5
LNG	ALK	Amine(PSF)	Methanation and liquefaction	LS-LPDF	388.9
LNG	PEM	DAC	Methanation and liquefaction	LS-LPDF	384.6
LNG	ALK	Amine(PSF)	Methanation and liquefaction	LS-HPDF	381.2
LNG	PEM	DAC	Methanation and liquefaction	LS-HPDF	377.9
Methanol	ALK	PSA(PSF)	Methanol synthesis	LSD	374.8
Methanol	ALK	DAC	Methanol synthesis	LSD	374.4
LNG	ALK	PSA(PSF)	Methanation and liquefaction	LS-LPDF	374.0
LNG	ALK	PSA(PSF)	Methanation and liquefaction	LS-HPDF	366.3
LNG	ALK	DAC	Methanation and liquefaction	LS-LPDF	356.4
LNG	ALK	DAC	Methanation and liquefaction	LS-HPDF	349.6
Ammonia	PEM	Cryo	Electric-based Haber-Bosch	LSD	314.7
Ammonia	PEM	PSA	Electric-based Haber-Bosch	LSD	314.7
Ammonia	ALK	PSA	Electric-based Haber-Bosch	LSD	292.9
Hydrogen	PEM		Liquefaction	LSD	290.2
Ammonia	ALK	Cryo	Electric-based Haber-Bosch	LSD	287.9
Hydrogen	ALK		Liquefaction	LSD	266.8
Ammonia	Standard NG production		SMR and Haber Bosch process	LSD	165.7

Hydrogen	Standard NG production		SMR and liquefaction	LSD	106.1
Hydrogen	Standard crude oil production		Naphtha cracking processes and liquefaction	LSD	106.1
Methanol	Standard NG production		SMR and methanol synthesis	LSD	101.2
HFO	Standard crude oil production		Standard refinery process	LSD	90.5
LNG	Standard NG production		Liquefaction	LS-LPDF	85.0
LNG	Standard NG production		Liquefaction	LS-HPDF	77.4

Table C-76. WtW GHG emissions(CO2 eq./MJ) based on selected fuel and technologies using the grid's mixed electricity in 2030

Fuel Type	**H_2**	**CO_2 and N_2**	**Conversion Process**	**Main propulsion system**	**WtW emission**
Ammonia	Standard NG production		SMR and Haber Bosch process	LSD	165.7
Methanol	PEM	Amine(PSF)	Methanol synthesis	LSD	152.0
LNG	PEM	Amine(PSF)	Methanation and liquefaction	LS-LPDF	149.6
Methanol	ALK	Amine(PSF)	Methanol synthesis	LSD	147.7
Methanol	PEM	PSA(PSF)	Methanol synthesis	LSD	147.5
LNG	PEM	PSA(PSF)	Methanation and liquefaction	LS-LPDF	146.8
LNG	PEM	Amine(PSF)	Methanation and liquefaction	LS-HPDF	146.0
LNG	ALK	DAC	Methanation and liquefaction	LS-HPDF	145.9
LNG	ALK	Amine(PSF)	Methanation and liquefaction	LS-LPDF	145.1
Methanol	ALK	PSA(PSF)	Methanol synthesis	LSD	143.1
LNG	PEM	PSA(PSF)	Methanation and liquefaction	LS-HPDF	143.1
LNG	ALK	PSA(PSF)	Methanation and liquefaction	LS-LPDF	142.3

LNG	ALK	Amine(PSF)	Methanation and liquefaction	LS-HPDF	141.5
LNG	ALK	PSA(PSF)	Methanation and liquefaction	LS-HPDF	138.7
Hydrogen	Standard NG production		SMR and liquefaction	LSD	106.1
Hydrogen	Standard crude oil production		Naphtha cracking processes and liquefaction	LSD	106.1
Methanol	Standard NG production		SMR and methanol synthesis	LSD	101.2
LNG	PEM	DAC	Methanation and liquefaction	LS-LPDF	98.6
LNG	PEM	DAC	Methanation and liquefaction	LS-HPDF	95.4
LNG	ALK	DAC	Methanation and liquefaction	LS-LPDF	94.1
Methanol	PEM	DAC	Methanol synthesis	LSD	90.9
HFO	Standard crude oil production		Standard refinery process	LSD	90.5
Methanol	ALK	DAC	Methanol synthesis	LSD	86.6
LNG	Standard NG production		Liquefaction	LS-LPDF	85.0
LNG	Standard NG production		Liquefaction	LS-HPDF	77.4
Ammonia	PEM	PSA	Electric-based Haber-Bosch	LSD	77.3
Ammonia	PEM	Cryo	Electric-based Haber-Bosch	LSD	76.1
Ammonia	ALK	PSA	Electric-based Haber-Bosch	LSD	73.1
Ammonia	ALK	Cryo	Electric-based Haber-Bosch	LSD	71.8
Hydrogen	PEM		Liquefaction	LSD	70.1
Hydrogen	ALK		Liquefaction	LSD	66.4

Table C-77. WtW GHG emissions(CO2 eq./MJ) based on selected fuel and technologies using the grid's mixed electricity in 2040

Fuel Type	H2	CO2 and N2	Conversion Process	Main propulsion system	WtW emission
Ammonia	Standard NG production		SMR and Haber Bosch process	LSD	165.7
Methanol	PEM	Amine(PSF)	Methanol synthesis	LSD	152.0
LNG	PEM	Amine(PSF)	Methanation and liquefaction	LS-LPDF	149.6
Methanol	ALK	Amine(PSF)	Methanol synthesis	LSD	147.7
Methanol	PEM	PSA(PSF)	Methanol synthesis	LSD	147.5
LNG	PEM	PSA(PSF)	Methanation and liquefaction	LS-LPDF	146.8
LNG	PEM	Amine(PSF)	Methanation and liquefaction	LS-HPDF	146.0
LNG	ALK	DAC	Methanation and liquefaction	LS-HPDF	145.9
LNG	ALK	Amine(PSF)	Methanation and liquefaction	LS-LPDF	145.1
Methanol	ALK	PSA(PSF)	Methanol synthesis	LSD	143.1
LNG	PEM	PSA(PSF)	Methanation and liquefaction	LS-HPDF	143.1
LNG	ALK	PSA(PSF)	Methanation and liquefaction	LS-LPDF	142.3
LNG	ALK	Amine(PSF)	Methanation and liquefaction	LS-HPDF	141.5
LNG	ALK	PSA(PSF)	Methanation and liquefaction	LS-HPDF	138.7
Hydrogen	Standard NG production		SMR and liquefaction	LSD	106.1
Hydrogen	Standard crude oil production		Naphtha cracking processes and liquefaction	LSD	106.1
Methanol	Standard NG production		SMR and methanol synthesis	LSD	101.2
LNG	PEM	DAC	Methanation and liquefaction	LS-LPDF	98.6
LNG	PEM	DAC	Methanation and liquefaction	LS-HPDF	95.4
LNG	ALK	DAC	Methanation and liquefaction	LS-LPDF	94.1
Methanol	PEM	DAC	Methanol synthesis	LSD	90.9

HFO	Standard crude oil production		Standard refinery process	LSD	90.5
Methanol	ALK	DAC	Methanol synthesis	LSD	86.6
LNG	Standard NG production		Liquefaction	LS-LPDF	85.0
LNG	Standard NG production		Liquefaction	LS-HPDF	77.4
Ammonia	PEM	PSA	Electric-based Haber-Bosch	LSD	77.3
Ammonia	PEM	Cryo	Electric-based Haber-Bosch	LSD	76.1
Ammonia	ALK	PSA	Electric-based Haber-Bosch	LSD	73.1
Ammonia	ALK	Cryo	Electric-based Haber-Bosch	LSD	71.8
Hydrogen	PEM		Liquefaction	LSD	70.1
Hydrogen	ALK		Liquefaction	LSD	66.4

Table C-78. WtW GHG emissions (CO_2 eq./MJ) based on selected fuel and technologies using the grid's mixed electricity in 2050

Fuel Type	**H_2**	**CO_2 and N_2**	**Conversion Process**	**Main propulsion system**	**WtW emission**
Ammonia	Standard NG production		SMR and Haber Bosch process	LSD	165.7
Methanol	PEM	Amine(PSF)	Methanol synthesis	LSD	114.2
Methanol	ALK	Amine(PSF)	Methanol synthesis	LSD	112.0
Methanol	PEM	PSA(PSF)	Methanol synthesis	LSD	111.6
LNG	PEM	Amine(PSF)	Methanation and liquefaction	LS-LPDF	110.3
LNG	PEM	Amine(PSF)	Methanation and liquefaction	LS-HPDF	109.5
Methanol	ALK	PSA(PSF)	Methanol synthesis	LSD	109.4
LNG	ALK	Amine(PSF)	Methanation and liquefaction	LS-LPDF	108.0
LNG	ALK	Amine(PSF)	Methanation and liquefaction	LS-HPDF	107.2
Hydrogen	Standard NG production		SMR and liquefaction	LSD	106.1
Hydrogen	Standard crude oil production		Naphtha cracking processes and liquefaction	LSD	106.1
LNG	PEM	PSA(PSF)	Methanation and liquefaction	LS-LPDF	104.6
LNG	ALK	DAC	Methanation and liquefaction	LS-HPDF	104.4
LNG	PEM	PSA(PSF)	Methanation and liquefaction	LS-HPDF	103.8
LNG	ALK	PSA(PSF)	Methanation and liquefaction	LS-LPDF	102.3
LNG	ALK	PSA(PSF)	Methanation and liquefaction	LS-HPDF	101.5
Methanol	Standard NG production		SMR and methanol synthesis	LSD	101.2
HFO	Standard crude oil production		Standard refinery process	LSD	90.5
LNG	Standard NG production		Liquefaction	LS-LPDF	85.0
LNG	Standard NG production		Liquefaction	LS-HPDF	77.4

LNG	PEM	DAC	Methanation and liquefaction	LS-LPDF	51.7
LNG	PEM	DAC	Methanation and liquefaction	LS-HPDF	50.8
LNG	ALK	DAC	Methanation and liquefaction	LS-LPDF	49.4
Methanol	PEM	DAC	Methanol synthesis	LSD	46.2
Methanol	ALK	DAC	Methanol synthesis	LSD	44.0
Hydrogen	PEM		Liquefaction	LSD	40.5
Ammonia	PEM	PSA	Electric-based Haber-Bosch	LSD	38.2
Ammonia	PEM	Cryo	Electric-based Haber-Bosch	LSD	37.4
Ammonia	ALK	PSA	Electric-based Haber-Bosch	LSD	36.0
Ammonia	ALK	Cryo	Electric-based Haber-Bosch	LSD	35.3
Hydrogen	ALK		Liquefaction	LSD	34.8

Table C-79. WtW GHG emissions(CO_2 eq./MJ) based on selected fuel and technologies using off grid (Windfarm) from renewable energy sources in the base year

Fuel Type	**H_2**	**CO_2 and N_2**	**Conversion Process**	**Main propulsion system**	**WtW emission**
Ammonia	Standard NG production		SMR and Haber Bosch process	LSD	174.2
Hydrogen	Standard NG production		SMR and liquefaction	LSD	106.08
Hydrogen	Standard crude oil production		Naphtha cracking processes and liquefaction	LSD	106.08
Methanol	Standard NG production		SMR and methanol synthesis	LSD	101.19
HFO	Standard crude oil production		Standard refinery process	LSD	90.49
LNG	Standard NG production		Liquefaction	LS-LPDF	85.02
Methanol	PEM	Amine(PSF)	Methanol synthesis	LSD	82.99
Methanol	PEM	PSA(PSF)	Methanol synthesis	LSD	82.97
Methanol	ALK	Amine(PSF)	Methanol synthesis	LSD	82.96
Methanol	ALK	PSA(PSF)	Methanol synthesis	LSD	82.94
LNG	PEM	PSA(PSF)	Methanation and liquefaction	LS-LPDF	79.69
LNG	ALK	PSA(PSF)	Methanation and liquefaction	LS-LPDF	79.66
LNG	PEM	Amine(PSF)	Methanation and liquefaction	LS-LPDF	79.60
LNG	ALK	Amine(PSF)	Methanation and liquefaction	LS-LPDF	79.57
LNG	Standard NG production		Liquefaction	LS-HPDF	77.38
LNG	PEM	PSA(PSF)	Methanation and liquefaction	LS-HPDF	72.04
LNG	ALK	PSA(PSF)	Methanation and liquefaction	LS-HPDF	72.01
LNG	PEM	Amine(PSF)	Methanation and liquefaction	LS-HPDF	71.95
LNG	ALK	Amine(PSF)	Methanation and liquefaction	LS-HPDF	71.92

Ammonia	PEM	Cryo	Electric-based Haber-Bosch	LSD	18.46
Ammonia	PEM	PSA	Electric-based Haber-Bosch	LSD	18.46
Ammonia	ALK	PSA	Electric-based Haber-Bosch	LSD	18.43
Ammonia	ALK	Cryo	Electric-based Haber-Bosch	LSD	18.43
LNG	PEM	DAC	Methanation and liquefaction	LS-LPDF	16.93
LNG	ALK	DAC	Methanation and liquefaction	LS-LPDF	16.90
Hydrogen	PEM		Liquefaction	LSD	13.86
Hydrogen	ALK		Liquefaction	LSD	13.83
Methanol	PEM	DAC	Methanol synthesis	LSD	11.15
Methanol	ALK	DAC	Methanol synthesis	LSD	11.12
LNG	PEM	DAC	Methanation and liquefaction	LS-HPDF	10.20
LNG	ALK	DAC	Methanation and liquefaction	LS-HPDF	10.17

Table C-80. WtW GHG emissions(CO_2 eq./MJ) based on selected fuel and technologies using off grid (Windfarm) from renewable energy sources in 2030

Fuel Type	**H_2**	**CO_2 and N_2**	**Conversion Process**	**Main propulsion system**	**WtW emission**
Ammonia	Standard NG production		SMR and Haber Bosch process	LSD	174.2
Hydrogen	Standard NG production		SMR and liquefaction	LSD	106.08
Hydrogen	Standard crude oil production		Naphtha cracking processes and liquefaction	LSD	106.08
Methanol	Standard NG production		SMR and methanol synthesis	LSD	101.19
HFO	Standard crude oil production		Standard refinery process	LSD	90.49
LNG	Standard NG production		Liquefaction	LS-LPDF	85.02
Methanol	PEM	PSA(PSF)	Methanol synthesis	LSD	80.86
Methanol	PEM	Amine(PSF)	Methanol synthesis	LSD	80.84
Methanol	ALK	Amine(PSF)	Methanol synthesis	LSD	80.82
Methanol	ALK	PSA(PSF)	Methanol synthesis	LSD	80.73
LNG	Standard NG production		Liquefaction	LS-HPDF	77.38
LNG	PEM	PSA(PSF)	Methanation and liquefaction	LS-LPDF	75.07
LNG	ALK	PSA(PSF)	Methanation and liquefaction	LS-LPDF	75.05
LNG	PEM	Amine(PSF)	Methanation and liquefaction	LS-LPDF	75.03
LNG	ALK	Amine(PSF)	Methanation and liquefaction	LS-LPDF	75.01
LNG	PEM	PSA(PSF)	Methanation and liquefaction	LS-HPDF	70.00
LNG	ALK	PSA(PSF)	Methanation and liquefaction	LS-HPDF	69.56
LNG	PEM	Amine(PSF)	Methanation and liquefaction	LS-HPDF	69.39
LNG	ALK	Amine(PSF)	Methanation and liquefaction	LS-HPDF	69.37

LNG	ALK	DAC	Methanation and liquefaction	LS-HPDF	62.84
Ammonia	PEM	PSA	Electric-based Haber-Bosch	LSD	14.40
Ammonia	ALK	PSA	Electric-based Haber-Bosch	LSD	14.38
Ammonia	PEM	Cryo	Electric-based Haber-Bosch	LSD	14.34
Ammonia	ALK	Cryo	Electric-based Haber-Bosch	LSD	14.33
LNG	PEM	DAC	Methanation and liquefaction	LS-LPDF	13.38
LNG	ALK	DAC	Methanation and liquefaction	LS-LPDF	13.36
Hydrogen	PEM		Liquefaction	LSD	11.07
Hydrogen	ALK		Liquefaction	LSD	11.06
Methanol	PEM	DAC	Methanol synthesis	LSD	8.68
Methanol	ALK	DAC	Methanol synthesis	LSD	8.66
LNG	PEM	DAC	Methanation and liquefaction	LS-HPDF	8.27

Table C-81. WtW GHG emissions(CO_2 eq./MJ) based on selected fuel and technologies using off grid (Windfarm) from renewable energy sources in 2040

Fuel Type	**H_2**	**CO_2 and N_2**	**Conversion Process**	**Main propulsion system**	**WtW emission**
Ammonia	Standard NG production		SMR and Haber Bosch process	LSD	174.2
Hydrogen	Standard NG production		SMR and liquefaction	LSD	106.08
Hydrogen	Standard crude oil production		Naphtha cracking processes and liquefaction	LSD	106.08
Methanol	Standard NG production		SMR and methanol synthesis	LSD	101.19
HFO	Standard crude oil production		Standard refinery process	LSD	90.49
LNG	Standard NG production		Liquefaction	LS-LPDF	85.02
LNG	Standard NG production		Liquefaction	LS-HPDF	77.38
Methanol	PEM	Amine(PSF)	Methanol synthesis	LSD	74.57
Methanol	ALK	Amine(PSF)	Methanol synthesis	LSD	74.56
Methanol	PEM	PSA(PSF)	Methanol synthesis	LSD	74.56
Methanol	ALK	PSA(PSF)	Methanol synthesis	LSD	74.55
LNG	PEM	PSA(PSF)	Methanation and liquefaction	LS-LPDF	66.91
LNG	ALK	PSA(PSF)	Methanation and liquefaction	LS-LPDF	66.59
LNG	PEM	Amine(PSF)	Methanation and liquefaction	LS-LPDF	66.58
LNG	ALK	Amine(PSF)	Methanation and liquefaction	LS-LPDF	66.57
LNG	PEM	PSA(PSF)	Methanation and liquefaction	LS-HPDF	62.96
LNG	ALK	PSA(PSF)	Methanation and liquefaction	LS-HPDF	62.95
LNG	PEM	Amine(PSF)	Methanation and liquefaction	LS-HPDF	62.94

LNG	ALK	Amine(PSF)	Methanation and liquefaction	LS-HPDF	62.93
LNG	ALK	DAC	Methanation and liquefaction	LS-HPDF	60.34
Ammonia	PEM	PSA	Electric-based Haber-Bosch	LSD	8.85
Ammonia	PEM	Cryo	Electric-based Haber-Bosch	LSD	8.85
Ammonia	ALK	PSA	Electric-based Haber-Bosch	LSD	8.84
Ammonia	ALK	Cryo	Electric-based Haber-Bosch	LSD	8.84
LNG	PEM	DAC	Methanation and liquefaction	LS-LPDF	8.19
LNG	ALK	DAC	Methanation and liquefaction	LS-LPDF	8.18
Hydrogen	PEM		Liquefaction	LSD	6.73
Hydrogen	ALK		Liquefaction	LSD	6.73
Methanol	PEM	DAC	Methanol synthesis	LSD	5.33
Methanol	ALK	DAC	Methanol synthesis	LSD	5.25
LNG	PEM	DAC	Methanation and liquefaction	LS-HPDF	5.01

Table C-82. WtW GHG emissions(CO_2 eq./MJ) based on selected fuel and technologies using off grid (Windfarm) from renewable energy sources in 2050

Fuel Type	**H_2**	**CO_2 and N_2**	**Conversion Process**	**Main propulsion system**	**WtW emission**
Ammonia	Standard NG production		SMR and Haber Bosch process	LSD	174.2
Hydrogen	Standard NG production		SMR and liquefaction	LSD	106.08
Hydrogen	Standard crude oil production		Naphtha cracking processes and liquefaction	LSD	106.08
Methanol	Standard NG production		SMR and methanol synthesis	LSD	101.19
HFO	Standard crude oil production		Standard refinery process	LSD	90.49
LNG	Standard NG production		Liquefaction	LS-LPDF	85.02
LNG	Standard NG production		Liquefaction	LS-HPDF	77.38
Methanol	PEM	Amine(PSF)	Methanol synthesis	LSD	71.82
Methanol	PEM	PSA(PSF)	Methanol synthesis	LSD	71.82
Methanol	ALK	Amine(PSF)	Methanol synthesis	LSD	71.82
Methanol	ALK	PSA(PSF)	Methanol synthesis	LSD	71.82
LNG	PEM	PSA(PSF)	Methanation and liquefaction	LS-LPDF	60.98
LNG	PEM	Amine(PSF)	Methanation and liquefaction	LS-LPDF	60.50
LNG	ALK	Amine(PSF)	Methanation and liquefaction	LS-LPDF	60.50
LNG	ALK	PSA(PSF)	Methanation and liquefaction	LS-LPDF	60.50
LNG	PEM	PSA(PSF)	Methanation and liquefaction	LS-HPDF	60.13
LNG	PEM	Amine(PSF)	Methanation and liquefaction	LS-HPDF	59.64
LNG	ALK	Amine(PSF)	Methanation and liquefaction	LS-HPDF	59.64

LNG	ALK	PSA(PSF)	Methanation and liquefaction	LS-HPDF	59.64
LNG	ALK	DAC	Methanation and liquefaction	LS-HPDF	58.60
Hydrogen	PEM		Liquefaction	LSD	5.64
LNG	PEM	DAC	Methanation and liquefaction	LS-LPDF	3.08
LNG	ALK	DAC	Methanation and liquefaction	LS-LPDF	3.08
LNG	PEM	DAC	Methanation and liquefaction	LS-HPDF	2.22
Hydrogen	ALK		Liquefaction	LSD	1.88
Ammonia	PEM	Cryo	Electric-based Haber-Bosch	LSD	0.99
Methanol	PEM	DAC	Methanol synthesis	LSD	0.90
Ammonia	PEM	PSA	Electric-based Haber-Bosch	LSD	0.83
Ammonia	ALK	Cryo	Electric-based Haber-Bosch	LSD	0.83
Ammonia	ALK	PSA	Electric-based Haber-Bosch	LSD	0.83
Methanol	ALK	DAC	Methanol synthesis	LSD	0.79

Section 7.3.4 GHG reduction potential of the emissions from total fleet using selected fuels

In this study, two future transport work demand scenarios were considered to assess the GHG emission reduction potential across the entire fleet using specific fuels. These scenarios are: a low growth scenario (OECD_RCP 2.6_G) and a high growth scenario (SSP2_RCP2.6_L).

The first table for each fuel displays the total GHG emission reduction (ΔE) achieved using energy-saving technologies, as determined by the method described in the supplementary material of Section 2.3.4.2.

To assess the impact of GHG reductions resulting from the introduction of new ships—specifically those aligned with SN_transport demand, SN_speed reduction, and SN_scrapping—using fuels such as HFO, LNG, methanol, hydrogen, and ammonia, annual GHG emissions and average GHG intensity for the base year, 2030, 2040, and 2050 were calculated. These calculations are presented in the second table for each fuel. This analysis assumes a single fuel type is used consistently across the fleet. This uniform approach aims to evaluate the individual effects of each fuel's adoption rather than exploring the implications of mixed fuel proportions, which come with greater uncertainties.

Unlike ammonia and hydrogen, which are carbon-free, both methanol and LNG contain carbon. The presence of carbon means that the Tank-to-Wake (TtW) emissions calculations for these fuels are influenced by the carbon's origin, be it fossil-based or renewable. For instance, when a fuel is synthesized using direct air capture (DAC) technology, the CO_2 released during combustion in the ship's engine isn't counted as part of the ship's emissions. This is because it essentially re-releases the same CO_2 back into the atmosphere. For clarity in assessing TtW emissions, the selected fuels (HFO, LNG, ammonia, and methanol) were categorized into three groups: 1) Fuels with fossil-based carbon. 2) Fuels with renewable carbon sources (CO2_DAC), and 3) Zero carbon fuels."

1. **Fuels with fossil-based carbon**

HFO

Table C-83. Total GHG emission reduction(ΔE) using HFO with energy-saving technologies

	Scenarios	2022	2030	2040	2050
Initial annual GHG emission (ton) (E_0)	Low growth	82,167,663	103,052,335	115,111,327	127,170,319
	High growth	82,167,663	115,826,376	143,852,919	171,879,462
	Low growth	0	15,597,469	23,454,059	32,245,922

Total amount of GHG emissions reduced (ΔE)	High growth	0	17,530,882	29,310,190	43,582,589

Table C-84. GHG reduction potential of the emissions using HFO

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	87,454,865	91,657,268	94,924,397
	High growth	82,167,663	98,295,493	114,542,729	128,296,873
Average GHG intensity (CO_2 eq./MJ)	Low growth	79.3	79.3	79.3	79.3
	High growth	79.3	79.3	79.3	79.3

LNG (LS-LPDF)

Table C-85. Total GHG emission reduction(ΔE) using LNG (LS-LPDF) with energy-saving technologies

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	99,214,611	105,036,309	106,481,039
	High growth	82,167,663	110,780,877	130,030,995	143,074,495
Total amount of GHG emissions reduced (ΔE)	Low growth	0	15,016,611	21,401,263	26,999,848
	High growth	0	16,767,222	26,493,958	36,278,662

Table C-86. GHG reduction potential of the emissions using LNG : LS-LPDF

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	84,198,000	83,635,046	79,481,191
	High growth	82,167,663	94,013,655	103,537,037	106,795,833
Average GHG intensity (CO_2 eq./MJ)	Low growth	79.3	73.0	67.1	60.1
	High growth	79.3	72.0	66.0	59.6

Methanol

Table C-87. Total GHG emission reduction(ΔE) using methanol with energy-saving technologies

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	100,191,307	109,487,092	118,355,778
	High growth	82,167,663	112,064,756	136,136,826	159,607,067
Total amount of GHG emissions reduced (ΔE)	Low growth	0	15,164,439	22,308,115	30,010,864
	High growth	0	16,961,543	27,738,028	40,470,741

Table C-88. GHG reduction potential of the emissions using methanol

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	85,026,868	87,178,976	88,344,914
	High growth	82,167,663	95,103,213	108,398,798	119,136,326
Average GHG intensity (CO_2 eq./MJ)	Low growth	79.3	76.8	70.0	66.9
	High growth	79.3	72.9	69.2	66.5

LNG (LS-HPDF)

Table C-89. Total GHG emission reduction(ΔE) using LNG (LS-HPDF) with energy-saving technologies

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	93,584,470	96,549,218	98,542,742
	High growth	82,167,663	103,379,709	118,388,422	132,022,905
Total amount of GHG emissions reduced (ΔE)	Low growth	0	14,164,462	19,672,009	24,986,975
	High growth	0	15,647,019	24,121,771	33,476,367

Table C-90. GHG reduction potential of the emissions using LNG : LS-HPDF

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	79,420,008	76,877,209	73,555,767
	High growth	82,167,663	87,732,690	94,266,651	98,546,538
	Low growth	79.3	71.0	64.9	59.5

Average GHG intensity (CO_2 eq./MJ)	High growth	79.3	69.6	63.5	58.9

2. **Fuels with renewable carbon (CO2_DAC)**

LNG (LS-LPDF)

Table C-91. Total GHG emission reduction(ΔE) using LNG (LS-LPDF) with energy-saving technologies

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	67,631,868	44,677,222	16,792,727
	High growth	82,167,663	69,260,160	47,226,660	18,207,513
Total amount of GHG emissions reduced (ΔE)	Low growth	0	10,236,410	9,103,033	4,258,045
	High growth	0	10,482,860	9,622,484	4,616,785

Table C-92. GHG reduction potential of the emissions using LNG : LS-LPDF

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	57,395,458	35,574,189	12,534,682
	High growth	82,167,663	58,777,300	37,604,176	13,590,728
Average GHG intensity (CO_2 eq./MJ)	Low growth	79.3	51.4	30.4	10.3
	High growth	79.3	46.3	25.2	8.1

Methanol

Table C-93. Total GHG emission reduction(ΔE) using methanol with energy-saving technologies

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	65,658,205	41,961,230	13,529,152
	High growth	82,167,663	66,665,101	43,500,416	13,663,754
	Low growth	0	9,937,687	8,549,647	3,430,517

Total amount of GHG emissions reduced (ΔE)	High growth	0	10,090,086	8,863,258	3,464,648

Table C-94. GHG reduction potential of the emissions using methanol

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	55,720,518	33,411,583	10,098,634
	High growth	82,167,663	56,575,015	34,637,159	10,199,106
Average GHG intensity (CO_2 eq./MJ)	Low growth	79.3	49.9	28.6	8.3
	High growth	79.3	44.6	23.2	6.1

LNG (LS-HPDF)

Table C-95. Total GHG emission reduction(ΔE) using LNG (LS-HPDF) with energy-saving technologies

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	64,618,683	40,350,005	14,494,152
	High growth	82,167,663	65,299,141	41,516,495	16,064,042
Total amount of GHG emissions reduced (ΔE)	Low growth	0	9,780,350	8,221,358	3,675,207
	High growth	0	9,883,341	8,459,031	4,073,276

Table C-96. GHG reduction potential of the emissions using LNG : LS-HPDF

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	54,838,333	32,128,648	10,818,944
	High growth	82,167,663	55,415,800	33,057,464	11,990,765
Average GHG intensity (CO_2 eq./MJ)	Low growth	79.3	50.7	29.0	9.6
	High growth	79.3	45.3	23.5	7.7

3. **Zero carbon fuels**

Ammonia

Table C-97. Total GHG emission reduction(ΔE) using ammonia with energy-saving technologies

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	68,545,060	45,646,364	13,250,959
	High growth	82,167,663	70,460,250	48,555,832	13,276,438
Total amount of GHG emissions reduced (ΔE)	Low growth	0	10,374,626	9,300,497	3,359,977
	High growth	0	10,664,500	9,893,304	3,366,438

Table C-98. GHG reduction potential of the emissions using ammonia

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	58,170,434	36,345,867	9,890,982
	High growth	82,167,663	59,795,750	38,662,528	9,910,000
Average GHG intensity (CO_2 eq./MJ)	Low growth	79.3	52.1	31.1	8.2
	High growth	79.3	47.1	25.9	5.9

Hydrogen

Table C-99. Total GHG emission reduction(ΔE) using hydrogen with energy-saving technologies

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	66,216,573	42,932,049	14,686,612
	High growth	82,167,663	67,399,483	44,832,640	15,275,661
Total amount of GHG emissions reduced (ΔE)	Low growth	0	10,022,199	8,747,452	3,724,008
	High growth	0	10,201,238	9,134,700	3,873,371

Table C-100. GHG reduction potential of the emissions using hydrogen

	Scenarios	2022	2030	2040	2050
Annual GHG emission (ton)	Low growth	82,167,663	56,194,374	34,184,597	10,962,603
	High growth	82,167,663	57,198,245	35,697,941	11,402,291

Average GHG intensity (CO_2 eq./MJ)	Low growth	79.3	50.3	29.2	9.1
	High growth	79.3	45.1	23.9	6.8

Section 7.4.1 Contribution to regulatory frameworks to evaluate GHG target attainment

Table C-101 Estimated annual GHG emissions and intensity from 10% ammonia uptake in the selected fleet

	Scenarios	2008	2022	2030
Annual GHG emission (ton)	Low growth	77,981,842	82,167,663	81,145,874
	High growth	77,981,842	82,167,663	90,016,354
Average GHG intensity (CO_2 eq./MJ)	Low growth	79.3	79.3	73.6
	High growth	79.3	79.3	72.6

Table C-102 Estimated annual GHG emissions and intensity from 10% LNG(LS_LPDF) uptake in the selected fleet

	scenarios	2008	2022	2030
Annual GHG emission (ton)	Low growth	77,981,842	82,167,663	80,978,438
	High growth	77,981,842	82,167,663	89,796,721
Average GHG intensity (CO_2 eq./MJ)	Low growth	79.3	79.3	73.5
	High growth	79.3	79.3	72.5

Table C-103 Estimated annual GHG emissions and intensity from 10% hydrogen uptake in the selected fleet

	Scenarios	2008	2022	2030
Annual GHG emission (ton)	Low growth	77,981,842	82,167,663	80,719,691
	High growth	77,981,842	82,167,663	89,457,170
Average GHG intensity (CO_2 eq./MJ)	Low growth	79.3	79.3	73.2
	High growth	79.3	79.3	72.2

Table C-104 Estimated annual GHG emissions and intensity from 10% methanol uptake in the selected fleet

	Scenarios	2008	2022	2030
Annual GHG emission (ton)	Low growth	77,981,842	82,167,663	80,617,916
	High growth	77,981,842	82,167,663	89,323,555
Average GHG intensity(CO_2 eq./MJ)	Low growth	79.3	79.3	73.1
	High growth	79.3	79.3	72.1

Table C-105 Estimated annual GHG emissions and intensity from 10% LNG(LS-HPDF) uptake in the selected fleet

	Scenarios	2008	2022	2030
Annual GHG emission (ton)	Low growth	77,981,842	82,167,663	80,427,164
	High growth	77,981,842	82,167,663	89,073,367
Average GHG intensity (CO_2 eq./MJ)	Low growth	79.3	79.3	73.0
	High growth	79.3	79.3	71.9

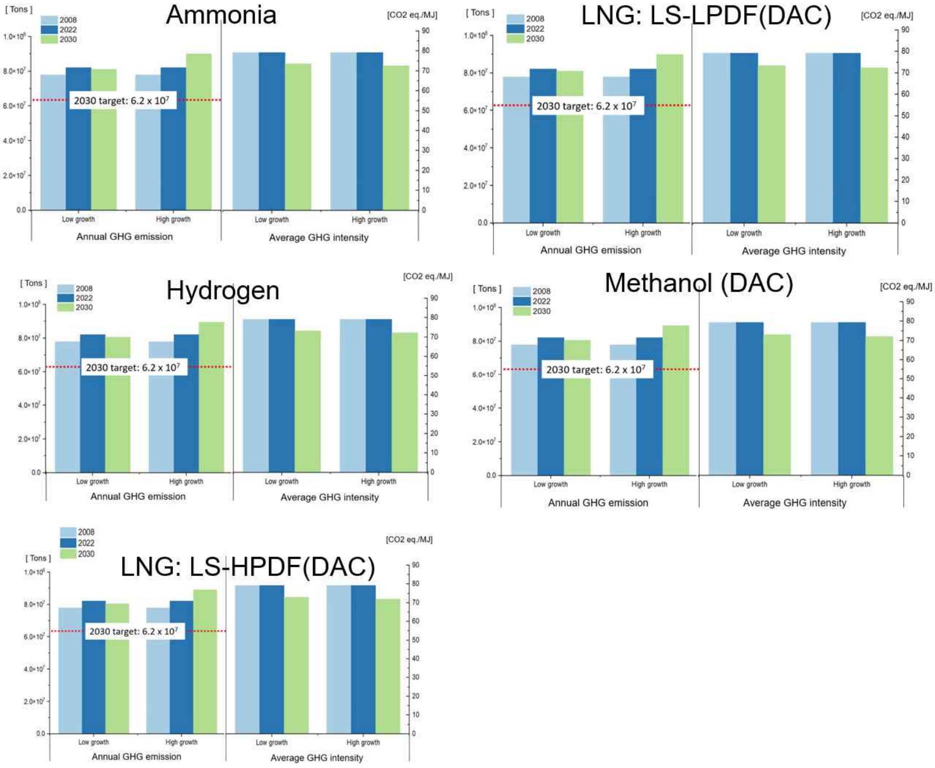

Figure C-5 Estimated annual GHG emissions and intensity from 10% uptake of selected fuels into the fleet

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