10-31-2022

Selection of the optimal alternative fuel in terms of the sustainability of the shipping industry through the multi-attribute decision making

Kyungrok Kim

WORLD MARITIME UNIVERSITY
Malmö, Sweden

SELECTION OF THE OPTIMAL ALTERNATIVE FUEL IN TERMS OF THE SUSTAINABILITY OF THE SHIPPING INDUSTRY THROUGH THE MULTI-ATTRIBUTE DECISION MAKING

By

KYUNGROK KIM
Republic of Korea

A dissertation submitted to the World Maritime University in partial fulfilment of the requirements for the award of the degree of

MASTER OF SCIENCE
in
MARITIME AFFAIRS

(MARITIME ENERGY MANAGEMENT)

2 0 2 2

Declaration

I certify that all the material in this dissertation that is not my own work has been identified and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views and are not necessarily endorsed by the University.

Signature: **.........**  **..........**

Date: **..............20th September 2022............**

Supervised by: **........Dr. Fabio Ballini.........**

Supervisor's affiliation: **.... World Maritime University....**

Acknowledgments

Throughout the writing of this dissertation, I have received a tremendous amount of support and assistance. Words cannot express my gratitude to my supervisor, Dr. Fabio Ballini, for his invaluable patience and feedback. You guided me to think critically from a comprehensive perspective, and your insightful feedback pushed me to sharpen my thinking and brought my work to a higher level.

I could not have undertaken this journey without my professors, Dr. Aykut I. Ölçer and Dr. Alessandro Schönborn. Additionally, this endeavor would not have been possible without tangible support from NSB Niederelbe Schiffahrtsgesellschaft mbH & Co. KG. I would like to extend my sincere thanks to my supervisor at the NSB group, Benedikt Gehensel. I am also thankful to Dr. Tuan Dong and my classmates for their advice, suggestions, and moral support, as well as the librarians and study mates from World Maritime University, who impacted and inspired me.

Furthermore, I would be remiss in not mentioning my parents, sister, and brother-in-law, for their wise counsel and sympathetic ear, as well as my niece, who will soon be out in the world. I tried to be your proud uncle in this process. In addition, I would also like to thank my pet, Ato, for all the entertainment and emotional support.

Particularly, I would like to thank my fiancée, Soyeong. You are always there for me, and your belief in me has kept my spirits and motivation high during this process. Even though my body is far away from you, my heart is always with you, and we will always be together wherever we are.

Abstract

Title of Dissertation: **Selection of the optimal alternative fuel in terms of the sustainability of the shipping industry through the multi-attribute decision making**

Degree: **Master of Science**

Green seaborne transportation strategies are needed to minimize the climate impact and economic loss of shipping. Various green strategies exist in maritime industries. Among these, using potential zero-emission fuels has garnered research and industrial interest. This study aims to select the optimal alternative fuel by measuring and evaluating four alternative marine fuels—liquefied natural gas (LNG), hydrogen, ammonia, and methanol—in terms of sustainability.

The assessment utilized the technique for order of preference by similarity to ideal solution analysis of the multi-attribute decision-making methodology to rank marine fuel options through life-cycle sustainability assessment: (i) environmental life-cycle assessment, greenhouse gas emissions impacting climate change, and acidification potentials; (ii) life-cycle cost and net present value (considering ship design to operation and decommissioning), and (iii) social life-cycle assessment (considering photochemical oxide creation potentials and human toxicity potentials, measuring air pollution levels that are lethal to humans and various marine organisms).

In all life-cycle sustainability assessments, the energy system model showed that the LNG-internal combustion engine (LNG-ICE) outperformed the other alternatives in terms of sustainability to achieve United Nations Sustainable Development Goals 3, 7, 13, and 14. The sustainability analysis revealed that the alternative fuel technologies were not considerably superior considering environmental, economic, and social multi-criteria evaluations. In addition, the scores of LNG-ICE, LNG-solid oxide fuel cell (LNG-SOFC), H_2-ICE, H_2-SOFC, and MeOH-SOFC, ranked from first to fifth, differed by a narrow margin.

LNG demonstrates technological feasibility, and LNG-fueled ships are now commercialized. The infrastructure of LNG for extraction, storage, delivery, and use is well established on major routes. However, LNG is a fossil fuel, and events such as oil shocks could recur due to regulations in countries with sizable natural gas reserves. Therefore, the technology development of H_2-ICE & SOFC and MeOH-SOFC, which are the most suitable technologies together with LNG, is essential.

KEYWORDS: Alternative fuels, Environmental life-cycle assessment, Life-cycle cost, Life-cycle sustainability assessment, Multi-attribute decision making, Social life-cycle assessment, Sustainability.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AP	Acidification Potential
CCS	Carbon Capture and Storage
CF	Characterized factor
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon dioxide
EGS	Exhaust Gas Scrubber
E-LCA	Environmental Life-cycle Assessment
EPU	Economic policy uncertainty
EU	European Union
FLL	Fuel Life-cycle Label
FC	Fuel Cell
GHG	Greenhouse Gas
GREET	United States Argonne National Laboratory's Greenhouse Gases, Regulated Emissions and Energy Use in Transportation
H_2	Hydrogen
HTP	Human Toxicity Potential
ICE	Internal Combustion Engines
IEA	International Energy Agency
IFO	Intermediate Fuel Oil
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LCA	Life-cycle Assessment

LCC	Life-cycle Cost
LCSA	Life-cycle Sustainability Assessment
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
NG	Natural Gas
NH_3	Ammonia
NOx	Nitrogen Oxides
NPV	Net Present Value
NO_2	Nitrogen Dioxide
N_2O	Nitrogen Oxide
MADM	Multi-attribute Decision-Making
MeOH	Methanol
PM	Particulate Matter
POCP	Photochemical Oxide Creation Potential
RE	Renewable energy
S-LCA	Social Life-cycle Assessment
SMR	Steam Methane Reforming
SOFC	Solid Oxide Fuel Cell
SO_2	Sulfur Dioxide
SOx	Sulfur Oxides
UN	United Nations
VLSFO	Very Low Sulfur Fuel Oil
VOCs	Volatile Organic Compounds

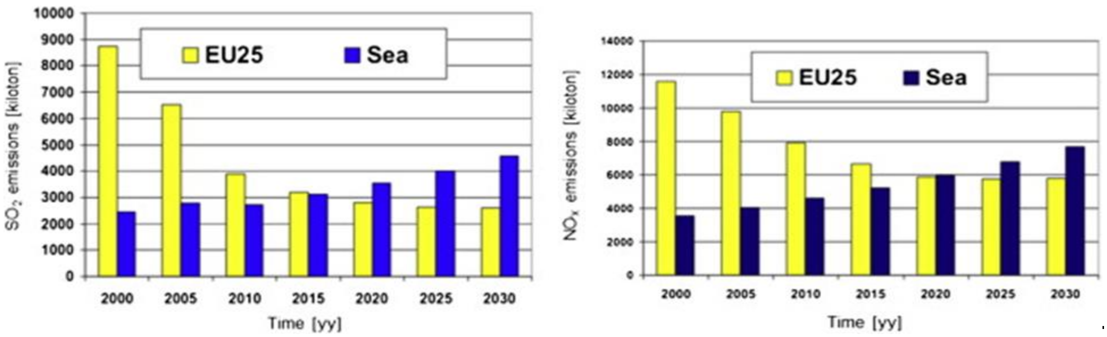
1. Introduction

1.1 Research Background

Vessels have been the center of the maritime industry because approximately 90 % of the world's trade is carried out by marine transport (Stannard, 2020). Ship exhaust contains toxic air pollutants and greenhouse gases (GHGs), e.g., CO_2, NOx, SOx, and PM, which are contributing to climate change and public health hazards (Clear Seas, n.d.). These ship-source pollutants—byproducts of fossil fuel combustion—can cause significant losses in terms of the three pillars of sustainability: environmental protection, economic viability, and social equity. The UN's sustainability concept presents an integrated perspective of environmental, social, and economic issues. According to this perspective, the present generation should meet its energy needs without hindering the successive generation's ability to fulfill its needs (United Nations (UN), n.d.). In this concept of sustainability, there are both positive externalities, such as knowledge, wealth, or health, and negative externalities, like the overuse of natural resources, harm to social cohesion, or overconsumption (Montiel et al., 2021). Hence, to help the maritime industry phase out the use of conventional fuel, this study examines four feasible alternative fuels—liquefied natural gas (LNG), hydrogen, ammonia, and methanol—in terms of sustainability through multi-attribute decision making (MADM).

Figure 1

SO_2 emissions from European Union land-based systems (EU25) vs. ship emissions (on the left); NOx emissions from EU25 vs. ship emissions (on the right)



Note. Adopted from "Improving sustainability of maritime transport through utilization of LNG for propulsion, 2013," by Burel et al., 2013.

As illustrated in Figure 1, the European Union's (EU's) land-based systems have significantly contributed to air pollution over the past 20 years. Fortunately, hazardous emissions from land-based emission sources are being regulated and reduced. However, as the marine trade volume rapidly increases, air pollution due to ship exhaust fumes has raised concerns worldwide. For instance, Čampara et al. (2018) stated that annual emissions from international trade vessels in the seas surrounding Europe had been estimated to contain 3.3 million tons of hazardous NOx, 2.3 million tons of SOx, and 250,000 tons of hazardous particulate matter (PM). Additionally, they estimated that ships' SOx and NOx emissions had increased by approximately 40–50 % between 2000 and 2020.

Furthermore, Clean Shipping Coalition (n.d.) predicted that "shipping is a major cause of harmful air pollution in Europe, and by 2020, shipping emissions of SO_2 and NOx could exceed the emissions of these pollutants from all other sources in the EU." According to the Paris Agreement, countries must voluntarily follow GHG reduction targets and initiate efforts outside the framework of the Climate Change Convention. The reason is that developing and developed countries have realized that GHG emissions are adversely impacting the acceleration of climate change.

1.2 Problem Statement

Air pollutants and GHG emissions from burning fossil fuels will have catastrophic effects on the environmental, economic, and social pillars of sustainable development. First, among the ship exhaust gases generated through conventional fuel combustion, SOx are acid gases that rise into the atmosphere and become a component of acid rain, which acidifies the land (Čampara et al., 2018). Further, NOx are powerful oxidizing agents that react with volatile organic compounds (VOC)s in the atmosphere and generate ozone (smog) on a hot summer day (United States Environmental Protection Agency (EPA), n.d.). The acid rain and ozone generated will further exacerbate climate change. Second, according to the World Health Organization (WHO, 2021), approximately 4.2 million persons die from outdoor air pollution annually, while 3.8 million persons die from household air pollution. In other words, one in eight persons worldwide dies from air pollution. Finally, Smith et al. (2015) estimated that ocean-going ships cause approximately

2.4 % of global anthropogenic GHG emissions (Smith et al., 2015). The International Maritime Organization (IMO) stated that these emission levels will increase in the future. GHGs emitted by ships mainly comprise CO_2, CH_4, and N_2O, of which CO_2 dominates the global warming potential (Winnes et al., 2015). Meanwhile, climate change caused by global warming is destroying ecosystems and endangered animals and plants (Peters, 1990).

The externality costs of energy supply and demand related to climate change and air pollution are at the level of $2.2–5.9 trillion per year (Anil et al., 2016). If air pollution and climate impact can be reduced by rapidly increasing the use of renewable energy (RE), it can save up to $4.2 trillion per year worldwide, more than 15 times the associated expenditure of doubling the share of renewables (Anil et al., 2016). To solve these problems, efforts to reduce petroleum production are being bolstered worldwide. In this context, whether the global economy and current energy system can adapt to shrinking oil production in terms of energy security must be considered. In other words, the adoption of optimal alternative fuel resources is essential from the perspective of the resilience of energy sources (Cherp & Jewell, 2011).

1.3 Research Objectives

This study aims to investigate the optimal alternative fuel by setting the environmental, social, and economic criteria for evaluating candidate fuels. Thus, it ranks four alternative fuel options—LNG, hydrogen, ammonia, and methanol—to determine the one that could meet the energy demands. For example, the methodology of this study is as follows.

1) The environmental life-cycle assessments (E-LCAs) of all four alternative fuel options are evaluated to address the environmental factors (environmental pillar).

2) The life-cycle cost (LCC) and net present value (NPV) are presented to consider the economic factors (economic pillar).

3) The social life-cycle assessment (S-LCA) for potential risks of alternative fuels to human health (social pillar).

Additionally, it will examine the technical applicability of the optimal alternative fuel selected in terms of sustainability to commercial vessels.

Furthermore, using the optimal alternative fuel would be the best way to help achieve UN Sustainable Development Goals (SDGs) 3 (Good Health and Well-being), 7 (Affordable and Clean Energy), 13 (Climate Action), and 14 (life below water).

The optimal alternative fuel obtained through this study will achieve several significant milestones:

1) UN SDGs 3 and 14: the number of patients with respiratory diseases is expected to decrease sharply by reducing air pollution with clean alternative fuels.

2) UN SDG 7: clean energy will improve access to clean and safe cooking fuels and technologies for 3 billion persons as well as the maritime industry, expand RE use beyond the electricity sector, and increase electrification in Sub-Saharan Africa.

3) UN SDG 13: CO_2 levels and other GHGs in the atmosphere can be drastically reduced by utilizing the optimal alternative fuel. Therefore, the optimal fuel can restrict a global temperature rise this century to below 2 °C above pre-industrial levels.

1.4 Research Questions

The following questions must be answered to meet this study's objectives.

1) Core question

   - Which propulsion technology using LNG, hydrogen, ammonia, and methanol is optimal in terms of environmental, economic, and social aspects?

2) Sub-question

- Is the optimal alternative fuel technically feasible from a sustainability perspective?

1.5 Key Assumptions and Limitations

The scientific consensus is that the use of conventional fuels is a significant cause of anthropogenic climate change. This warrants the proposal and use of an optimal alternative fuel for the decarbonization of industries.

However, well-to-wake (WtW) data from the LCA software GREET is insufficient. Therefore, the author believes the best way to obtain results from the LCA methodology would be to combine values from the extant literature and GREET. Moreover, the Global Warming Potential 100 (GWP-100) values are only updated occasionally. This change in the GWP-100 value, which can affect the environmental evaluation of alternatives, can be attributed to a scientific estimate of the energy absorption or lifetime of the gases, or a change in the atmospheric concentration of GHGs, resulting in an additional change in energy absorption of one ton of gas.

Furthermore, because this research is limited to a specific period in 2022, and the social operations of that year, including the economy and social trends, may have affected the research results. Additionally, due to data limitations, all possible alternative fuels could not be analyzed and compared. Further, a limited number of professionals and stakeholders could be interviewed. These limitations affected the research conclusions.

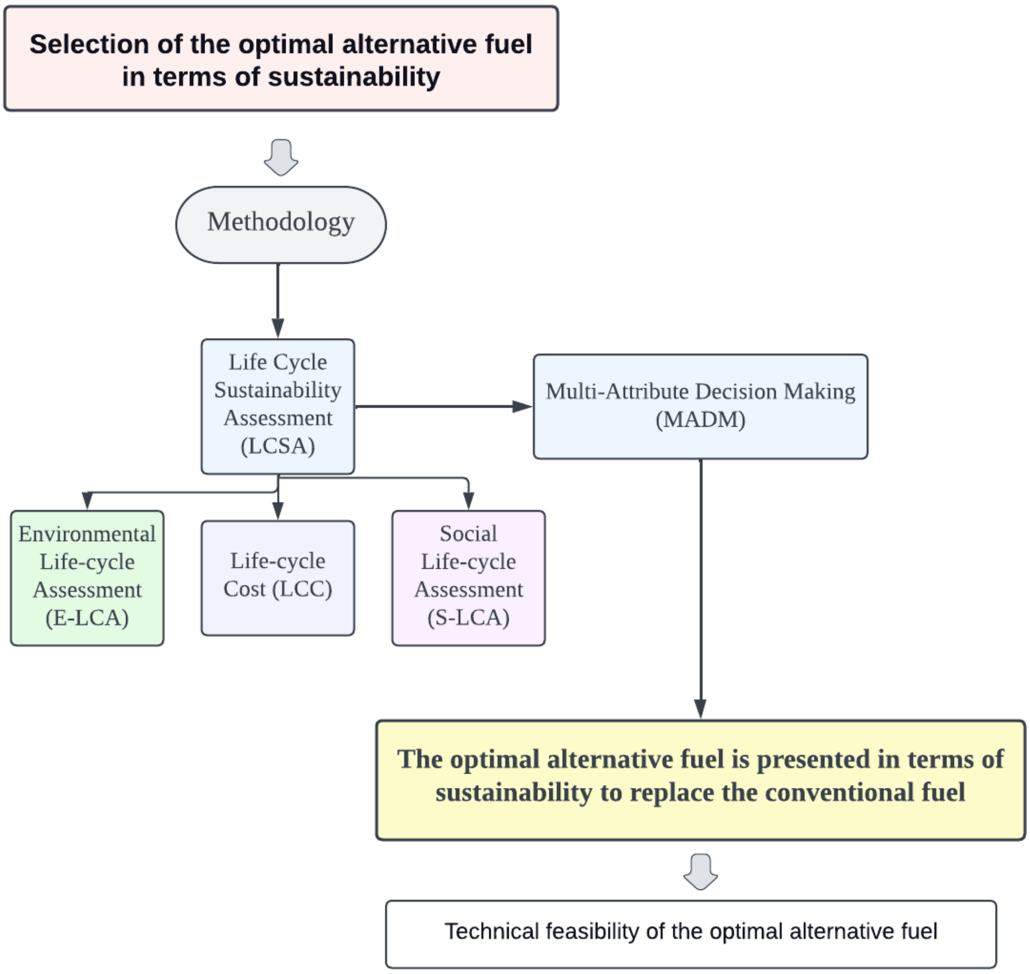
1.6 Methods

This study uses qualitative and quantitative methods as primary and secondary sources based on GREET and values from the research literature. A primary source is MADM, which is a quantitative method. Further, to support MADM, life-cycle sustainability assessment (LCSA) and peer-reviewed literature surveys show both quantitative and qualitative as secondary sources. For example, the technique for order of preference by similarity to ideal solution (TOPSIS) of the MADM methodology was utilized for analyzing the results, allowing the author to compare and rank different alternative fuel options using LCSA methodologies. The author collected secondary data through GREET and comprehensive desk-side surveys of the journal articles from ScienceDirect and Google Scholar and other official organizations' and societies' websites such as the UN, IMO, Lloyd's Register, DNV-GL, ABS, etc. Previous publications in the WMU library were reviewed for hard and soft copies.

1.7 Research Outline

Figure 2

Flowchart of the research approach taken to select the optimal alternative fuel



Note. Developed by Author (2022).

This article consists of six chapters. Chapter 1 introduces the context and problem statements about ships' air pollutants and GHG emissions. Further, it presents the research objectives and the fundamental assumptions and limitations of the study. Chapter 2 reviews the extant literature on alternative fuels and sustainability to obtain clues on how to mitigate the effects of fossil fuels. Chapter 3 details the evaluation method and alternative fuels in terms of sustainability. Chapter 4 presents the results of the LCSA analysis using MADM. Chapter 5 explores the technical feasibility of the selected alternative fuel. Chapter 6 summarizes the conclusions and recommendations. A flowchart of the research is illustrated in Figure 2.

Although humans have made technological advances that significantly contributed to social development through conventional fuels, these developments are simultaneously causing disasters such as climate change and affecting the economy and environment. Recognizing these disadvantages associated with conventional fuels for the sustainable development of the marine industry, this paper selects the optimal fuel from LNG, hydrogen, ammonia, and methanol, which have been identified through recent research as alternatives to replace the existing fuel. Furthermore, the technological feasibility of selected optimal alternative fuel is reviewed to examine the possibility of technological development and to provide directions for future research, contributing to the benefit of the environment, economy, and socially sustainable maritime industry.

2. Literature Review

2.1 General

Worldwide trade is increasing annually and should continue to do so in the foreseeable future. Accordingly, maritime transportation derived from trade has also increased. Consequently, freight ships, which support approximately 78 % of the world's maritime transportation, consume massive amounts of fossil fuels (Ma, 2020). In this context, maritime transport will continue to increase. Several studies have demonstrated sustainability with new clean energy for shipping, which is essential to prevent the catastrophic effects of fossil fuel combustion. Other studies have attempted to find the optimal alternative fuel, albeit under conflicting objectives.

Çetin and Sogut (2021) stated that the government and the shipping industry of the country would have different perspectives on environmental protection due to the unique externality of maritime economics. For example, a government may aim to eliminate fossil fuels, whereas the shipping companies insist on optimizing the level of emissions by burning fossil fuels instead. Therefore, their study focused on the importance of sustainable indicators and developing companies' energy efficiency policies for ship management.

Hansson (2020) focused on the need to produce fuels from RE sources by identifying those conventional marine fuels that benefited the environment, rather than LNG and methanol produced from fossil fuel energy sources. Therefore, Hansson (2020) compared the fuel options to identify the optimal alternative fuel through conflicting objectives, as listed in Table 1. Table 1 indicates that battery-powered electric propulsion is an efficient fuel option to utilize onboard ships. However, Hansson found that it could only power smaller vessels.

Table 1

Prerequisites for different low and potential zero-carbon marine fuels; ICE: internal combustion engine, FC: fuel cell

Fuel option	Technical maturity	Use in ICE and FC?	Cost: Fuel cost/Capital cost	Production potential	Safety	Possible sailing distance
Methanol	Medium	Yes	Medium/ Medium	Medium	Low risks	Medium
Biodiesel	High	ICE only	Medium/ Low	Medium	Low risks	Long
LBG	Medium	Yes	High/ Medium	Medium	Low risks	Medium
Hydrogen	Low	Yes	High/ Medium	High	Risks	Short
Ammonia	Low	Likely	High/ Medium	High	Risks	Medium
Batteries	Medium	n.a.	Low/High	Medium	Low risks	Short

Note. Adapted from "Navigating towards low and potential zero carbon marine fuels," by Hansson, 2020. Copyright 2020 by Hansson, J.

Furthermore, Ashrafi et al. (2022) believe that efforts to decarbonize the marine industry rely on various innovative solutions, such as alternative fuel supply bunkering, new ship design, and more efficient operation strategies. Therefore, the authors emphasized the necessity to transition to low- and zero-carbon fuels to achieve the targets set by the IMO. Because technical and operational efficiency measures alone cannot achieve target emissions, their study provided decision-makers with a platform based on the need to include and integrate environmental, economic, and social factors for marine fuel sustainability to understand the priorities and interests of stakeholder groups in marine fuel selection. Moreover, the authors urged academia and marine experts worldwide to share knowledge and appeal for stakeholder participation to contribute to the development of practical sustainability policy standards.

In this scenario as mentioned above, alternative fuels that can replace conventional fuels are needed to achieve the goals of international organizations to prevent climate change. Otherwise, air pollutants generated by burning fossil fuels will cause health hazards. This necessitates the selection of the optimal alternative fuel in terms of environmental, economic, and social aspects—the three pillars of sustainability—and appropriate investment in technologies suitable for the selected alternative fuel.

2.2 Conventional Fuel's Effect from a Sustainability Perspective

The IMO has been addressing marine pollution from vessels as a primary concern since 1973. The seriousness of marine pollution overshadowed air pollution due to ship emissions because no visually significant damage, such as oil spill accidents, ensues from air pollution (IMO, n.d.). Therefore, it does not generally interest—or draw consultations from—stakeholders and the public. However, technological advances in air pollutant detection have led research institutions to identify SOx and NOx as primary constituents of ship emissions—two of the most hazardous pollutants in the atmosphere.

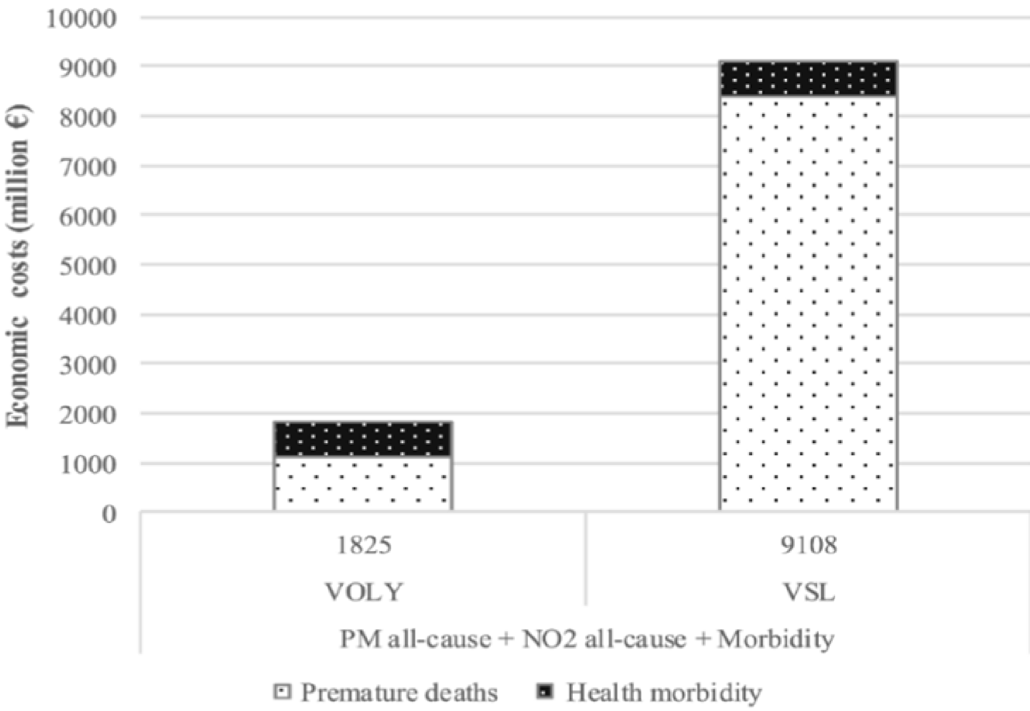
As stated above, based on the findings of the scientific community, the IMO surmised that air pollution and GHG emission could impose a cumulative effect on the natural environment, economy, and human health. Therefore, the IMO adopted the International Convention for the Prevention of Marine Pollution from Ship (MARPOL) Annex VI in 1997 and has since been amending it according to new scientific data. Furthermore, the IMO has attempted to coordinate with all UN Member States to prevent the adverse impacts of air pollution. Consequently, the IMO and all UN Member States adopted the 2030 Agenda for Sustainable Development in 2015 to establish the peace and security of the world. This agenda has 17 SDGs, which do not require a transformation of the financial, economic, and political systems that manage global societies to ensure the human rights of all people (UN, 2020). However, organizations such as the UN and IMO have made little progress in this effort. For that reason, this section examines why it has been difficult to prevent air pollution from ships despite the efforts of the IMO and analyzes the causes and consequences of air pollution in terms of the environmental, economic, and social pillars of sustainable development.

The effects of GHG emissions are becoming more severe because maritime traffic continues to be the center of global trade. If this situation is allowed to persist, hazardous substances from ships, such as CO_2, CH_4, and N_2O, will have a harsher impact on sustainability. Moreover, according to the latest Intergovernmental Panel on Climate Change (IPCC) Report, the effects of climate change will increase in the subsequent decades as the earth becomes hotter from global warming due to GHG emissions from ships. This increasingly abnormal climate phenomenon is causing several changes that vary with region, including “changes to wetness and dryness, to winds, snow, and ice, coastal areas and ocean” (“Some climate change,” 2021). Especially, climate change causes massive wildfires, hurricanes, droughts, and floods. Moreover, at the current rate, global temperatures are expected to rise by 3.2 °C by the end of this century. Therefore, the Paris Agreement stated that GHG emissions must be decreased by 7.6 % each year from 2020 to constrain the global temperature by 1.5 to 2.0 °C from the current temperature. Although human activity in 2020 had drastically reduced owing to the COVID-19 pandemic, the drop in emissions (6 %) fell short of the target of 7.6 % (UN, 2020).

In addition to the environmental pillar, the economic pillar has not been considered in the literature. As mentioned above, air pollutants such as NOx and SOx directly damage the environment and human health. They also have an impact on the economy. Nunes et al. (2021) estimated the economic costs of disease-causing air pollutants (PM and NO_2) to be approximately 9,100 million € yr-1 (for the value of statistical life approach (VSL)) and 1,825 million € yr-1 (for the value of life year approach (VOLY)) (Figure 3). Further, approximately 3,475 million € yr-1 (with the VSL approach) and 851 million € yr-1 (with the VOLY approach) were estimated for PM2.5-led mortality by cause. The VSL and VOLY approaches accounted for 0.72 % and 0.15 % of the Iberian Peninsula's gross domestic product in 2015 due to the burden of all causes of PM and NO_2, respectively. Moreover, PM2.5 has a specific mortality rate and costs approximately 0.28 % and 0.06 % for the VSL and VOLY approaches, respectively (Nunes et al., 2021). These results demonstrate that air pollution from ships significantly impacts health and related costs.

Figure 3

Total costs of the all-cause economic burden of disease related to shipping air pollution for the Iberian Peninsula in 2015



Note. Adopted from "Estimating the health and economic burden of shipping related air pollution in the Iberian Peninsula. Environment International, 2021," by Nunes et al., 2021.

In addition to the environmental and economic pillars, the social pillar is also an essential part of air pollution from ships. The public is a vital factor in constructing a social base. Air pollution from ships threatens human health as it causes various respiratory diseases and conditions. For instance, PM from a ship's exhaust combines fine soot particles with fuel combustion products and ash formed by liquid droplets. Further, SOx particles reach the atmosphere and form small aerosol compounds, while most are formed in the atmosphere by complex reactions with chemicals such as NOx. People inhale these minuscule, harmful particles, which severely damages their health. For example, a study by Backes et al. (as cited by Mannucci & Franchini, 2017) revealed that "air pollution can affect the developing fetus via maternal exposure, resulting in preterm birth, low birth weight, growth restriction, and potentially adverse cardiovascular and respiratory outcomes" (p.3). Further, air pollution can lead to inflammation, which eventually leads to heart and lung failures (Clean Shipping Coalition, n.d.). Moreover, air pollution can harm the skin as air pollutants (e.g., NOx and PM) destroy the ozone layer and allow ultraviolet radiation (UVR), increasing the possibility of pigmentation on the skin increases. Furthermore, organ damage was also observed as contaminants seeped into the pores of the skin (Manisalidis et al., 2020).

In the worst cases, air pollution from ships has been associated with increased mortality. Recent scientific studies found that soot emissions from international shipping kill approximately 50,000 persons annually in Europe. As per Clean Shipping Coalition (n.d., p.3), "through chemical reactions in the air, SO_2 and NOx are converted into tiny airborne particles, sulfate and nitrate aerosols." These tiny particles in the air contribute to premature death because they are small enough to enter the bloodstream through the lungs and tissues. Shag et al. (as cited by Mannucci & Franchini, 2017) concluded that "each 10 μg/m3 increase in PM2.5 was associated with a 0.38 % increase in total mortality, a 0.51 % increase in respiratory mortality, and a 0.44 % increase in cardiovascular mortality" (p.2).

These data led us to infer that marine fuel oil burned by vessels appears to be the primary source of air pollutants and GHGs that threaten the environment, economy, and health. Hence, ships' fuel systems must be replaced with cleaner alternatives. Furthermore, as mentioned before, the IMO proposed the implementation of relevant regulations to prevent air pollution from ships. In particular, the Clean Shipping Coalition (n.d.) estimates that tightening the ship fuel sulfur standards agreed upon by the IMO in 2008 would save up to 26,000 lives a year in the EU in 2020. Therefore, the IMO's efforts to strengthen discipline should be continued. Consequently, in recent years, the use of an exhaust gas scrubber (EGS) has been considered a viable means to meet the requirements of Annex VI because the device's primary benefit is it allows to use heavy fuel oil (HFO) while preventing emissions of air pollutants. However, with the strengthening of the requirements of Annex VI after 2020, the price of HFO might fluctuate as "sulfur content should drop to 0.5 %" (Nižić et al., 2017, p.60). For this reason, the use of EGS is not economical.

To summarize, air pollutants and GHGs caused by marine fuel oil combustion from ships are burdening the three pillars of sustainability. Regarding the environment, ships emit GHGs such as CO_2, CH_4, and N_2O by burning conventional fuel. Consequently, the earth's temperature continues to increase. Regarding the economic pillar, air pollution from ships has markedly damaged the economy, with human diseases caused by air pollutants from vessels. Moreover, the cost of treating people suffering acute respiratory diseases from air pollution is high. Finally, in terms of the social pillar, people working around ships and harbors are developing respiratory diseases due to air pollutants from ships. The total reduction of air pollution from ships, however, may not be possible without damaging the economy, as shipping is the backbone of world trade. Therefore, the three pillars must be balanced with one another for sustainable development. As a solution, the use of alternative fuels should be encouraged by finding optimal alternative fuels in terms of sustainability.

2.3 IMO and EU Actions

Anthropogenic climate change has been endangering human rights and invalidating global health and poverty reduction efforts since the Industrial Revolution. As mentioned earlier, it is mostly caused by burning fossil fuels. Fossil fuels have been used to generate electricity. Since the Industrial Revolution, its usage has only soared. Climate change most significantly affects the economically backward strata. Especially, the least developed countries will suffer the most from floods, wildfires, food insecurity, and forced migration, even in the best scenario. For example, as per a UN report (UN, 2019), 18.8 million persons in 135 countries were displaced in 2017 due to climate change (UN, 2019). This is near twice the number displaced by conflicts during the same year. Furthermore, by 2050, 140 million persons in Sub-Saharan Africa, South Asia, and Latin America alone will be displaced because of climate change-induced disasters (UN, 2019). Based on its current track, climate change will render the global economy fragile, pushing hundreds of millions of persons into poverty. Therefore, addressing climate change will build a new framework—one without fossil fuel emissions and waste production—for the global economy that should reduce poverty and improve economic well-being. This new framework should provide economic prosperity, decent work, and environmental sustainability.

To deal with these catastrophes, IMO enacted MARPOL Annex VI, Chapter 4, Energy Efficiency Regulation, to control GHG emissions, which is the technical and operational section of the command-and-control policy focused on ships and management. For example, according to MARPOL Annex VI, Chapter 4, Regulations 20 and 21, the EEDI requires a minimum energy efficiency per capacity mile for different ship types and size segments (Zabi, 2020). Furthermore, EU foreign affairs ministers approved conclusions on the outcome of the COP26 climate conference and agreed on the EU priorities for working on climate diplomacy in February 2022. They also called for other developed countries to fulfil their collective commitments to mobilize $100 billion (approximately 84 billion euros) annually, and for multilateral development banks and international financial institutions to mobilize the private sector and shift the global financial flows to sustainable and green investments (EU, n.d.). To summarize, the EU and its Member States will, as per reports, work with partners worldwide to accelerate the implementation of measures and initiatives agreed upon at the COP26 in a joint European team approach (EU, n.d.).

In addition, several EU projects are researching the technical feasibility of alternative fuels. For instance, Appendix 1 highlights the current projects of Nordic Energy Research (NER), which is attempting to develop technologies that will use alternative marine fuels. Another example is CHEK, a project supported by the European Union's Horizon 2020 program and proposed to aim for zero-emission delivery. The project will develop and demonstrate two custom ship designs: a bulk carrier optimized for wind energy and a hydrogen-powered cruise ship. The innovative ships will use interdisciplinary combinations of innovative technologies to reduce greenhouse gas emissions by 99 % and achieve energy savings by at least 50 % (CHEK, n.d.).

Moreover, there are responses to regulating air pollutants emissions such as NOx and SOx that cause not only human health issues but also acid rain and sea and soil acidification. Emission controls have been established to restrict the emission of SOx and PM by limiting the maximum sulfur content in the vessels' fuel loaded and bunkered, and subsequently used onboard (IMO, n.d.). For instance, according to the global regulations of the IMO, 0.5 % m/m sulfur content (global sulfur limit) regulation since 1 January 2020 as outlined by MARPOL Annex VI, Chapter 3, Regulation 14 (IMO, n.d.). Controls for sulfur content are different inside and outside of the emission control areas (ECA), where the sulfur content of any fuel onboard has been required to not exceed 0.1 % m/m since 1 January 2015. In addition, ships have been required to comply with the NOx Tier III emission regulations since 1 January 2016, as outlined by MARPOL Annex VI, Chapter 3, Regulation 13 (IMO, n.d.).

2.4 Alternative Fuel Options

As international rules continue to be tightened to prevent environmental pollution, alternative fuels must be used instead of fossil fuels to deal with these air pollutants and GHG emissions from ships. Therefore, the utilization of alternative fuels should penetrate the power system onboard vessels to alleviate the effect of climate change and human health crises caused by the emission of air pollutants and GHGs from combustion. Several production processes exist for alternative fuels, the common requirement among all being no additional emissions of CO_2. Particularly, liquid as well as a few gaseous fuels are deemed the most promising solutions for seaborne trade, while solid fuels can be used for stationary requirements at power plants (Stančin et al., 2020). However, most alternative fuels are not commercially viable due to the production or consumption process and technological limitations. This is primarily attributed to the high energy penalty incurred on fuels during their life cycle, or the environmental and economic viability of the production process itself (Stančin et al., 2020). Accordingly, several studies have examined the feasibility of LNG, hydrogen, ammonia, and methanol as alternative fuels.

LNG can be a suitable replacement for existing conventional fuels, like intermediate fuel oil. Because LNG does not contain SOx and PM and emits approximately 90 % less NOx than conventional fuels (Tam et al., 2019), it could help several stakeholders protect themselves from not only regional emission standards but also future regulations. However, one of the main concerns about LNG-fueled vessels is the cost of bunkers. LNG prices continue to increase based on historical price changes. Therefore, experts have predicted that LNG prices will remain relatively high throughout 2022. For example, according to market research, lack of new supplies and reduced investment have caused supply-side constraints in the global LNG market in recent years, with the most significant producers operating close to their total capacities. In the last week of June 2022, the LNG prices increased by ~60 % and are expected to exceed $40 per million British thermal units (mmBtu) within a short period (Marwa, 2022). Moreover, the methane slip problem due to unburned methane of the engine may be a fatal defect of LNG mainly composed of CH_4. Nevertheless, the latest technologies can significantly alleviate this problem (Lindstad & Rialland, 2020). Therefore, according to data in the literature, LNG is still a promising alternative fuel as it can reduce NO emissions by more than 50 %, while maintaining output and efficiency.

Hydrogen-fueled engines can help decarbonize the industry. It will help reduce not only CO_2 emissions but also other air pollutants such as unburnt hydrocarbons, aromatic compounds, sulfur oxides, soot, and smoke (Alkhaledi et al., 2022). Therefore, the use of hydrogen as a fuel can provide impetus to climate change deceleration and strengthen SDG 13 (climate action). A promising piece of technology to operate hydrogen-fueled engines is the hydrogen-polymer electrolytic membrane fuel cell (PEMFC). Alaswad et al. (2016) demonstrated the many advantages of a PEMFC, including high electrical efficiency, silence, low pollutant emissions, ease of installation, and rapid ignition (Diaz et al., 2014). However, since PEMFC requires 99.97% hydrogen purity (Staffell et al., 2019), it would be feasible only when the technology and infrastructure to produce adequate amounts of green-hydrogen are established. Further, hydrogen is not the best option for deep-sea shipping because the storage of hydrogen requires a sizeable volume due to the element's low caloric value of hydrogen. Additionally, it could have a significant explosion hazard.

Ammonia is another potential zero-carbon fuel that can reduce the climate impact of shipping if produced by RE sources (Hansson et al., 2020). Hansson et al. (2020) stated that the chemical was demonstrated as a fuel for compression ignition (CI) engines, spark ignition (SI) engines, and fuel cells. Ammonia has specific advantages. First, it is carbon-free, so it has no direct GHG effect. Second, its energy density is 22.5 MJ/kg, compared to that of fossil fuels; for example, low-ranked coals have approximately 20 MJ/kg, natural gas (NG) 55 MJ/kg, LNG 54 MJ/kg, and hydrogen 142 MJ/kg. Last, by compression to 0.8 MPa at atmospheric temperature, ammonia can be effortlessly liquefied (Valera-Medina et al., 2021). However, it also has some disadvantages. For instance, it is toxic, so it can cause fatalities when inhaled. When exposed to a high concentration of ammonia, the mucous membrane rapidly absorbs it, destroying the cell tissue to a lethal degree.

Finally, methanol is another alternative fuel option with a high potential for use in marine engines because of its inherent advantages (IEA, n.d.). For example, it cools down the intake air, in return allowing for a higher amount of fuel to be combusted. Thus, the compression ratio can be improved, and high-performance engines can be designed. Furthermore, it does not form carbon-to-carbon bonds and has a high oxygen content, which theoretically leads to soot-free combustion. Methanol is suitable for Otto engines as it has a large octane number and high knocking resistance. Further, it has an octane rating that is considerably higher than that of gasoline. In other words, methanol causes minor engine knock or preignition generation, owing to strong cooling effects from the high-octane rating and latent heat. These advantages make it suitable for the spark-ignition Otto engine fuel (Tunér et al., 2018). However, Saxena et al. (2021) proved that, in the dual fuel operation of the methanol engine, the fuel premixing range is limited by higher pressure increments, partial combustion, misfire, and knocking. In addition, an increase in the methanol fuel premixing ratio results in a more considerable cyclic combustion change.

This discussion led us to conclude that no single option is perfect for shipping propulsion. They all have merits and demerits in terms of sustainability. Moreover, studies have not rigorously compared LNG, hydrogen, ammonia, and methanol with respect to the environmental, economic, and social goals to boost UN SDGs 3, 7, 13, and 14. Hence, by studying the optimal alternative fuel in terms of sustainability, future research could explore methods to improve strategies for reducing the impact of GHGs, and reduction of the amount of air pollutants will prevent climate action. Therefore, this study focuses on four fuel options (LNG, hydrogen, ammonia, and methanol) from three aspects of sustainability (environment, economic, and social goals).

2.5 Drivers and Barriers to Sustainable Governance

Several legal barriers are preventing the implementation of alternative fuels despite the many drivers. This chapter introduces the drivers and barriers to alternative fuels in the maritime sector. As indicated in Table 2, decision-makers are struggling to instill changes to phase out conventional fuel.

Table 2

Drivers and barriers to alternative fuels

Sustainability	Driver	Barrier
Environment	GHG impacts	Policymakers are struggling to reduce the impact of GHG from seaborne transportation through legal methods such as carbon taxes and shipping congestion charges because of the ethical concerns related to these methods.
Economy	Sustainable management	From the perspective of the shipping industry, immediately benefiting from the changes is not easy from the aspect of net present value when operating alternative fuel propulsion ships; therefore, the industry is attempting to operate ships on conventional fuels without violating international laws.
Social	Healthy life	Creating awareness among the public on how air pollutants emitted by ocean transport are destroying the healthy living of people and aquatic life is a challenge. In addition, the unintended consequences of social policy have aroused antipathy toward sustainable social policy.

Note. Developed by Author (2022) using data from Ministry of the Environment, Government Offices of Sweden (2020) and Rivera et al. (2017).

Furthermore, Khan and Su (2022) evaluated the impact of economic policy uncertainty (EPU) on renewable energy (RE) in G7 countries, including Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States, using the wavelet quantile-on-quantile (QQ) method, and reported that EPU negatively affects RE. For example, the 2011 Fukushima nuclear accident triggered faster changes and phased elimination of nuclear power. EPU threatens RE growth, and the development RE has been slow since 2014 because it has been unable to produce sufficient electricity to respond to climate change (Dalby et al., 2018). Likewise, the sector experiences financial constraints, and investors have adopted risk aversion policies that have dampened future investments. Sustainable development of alternative fuels is in the same vein as that of RE because both involve the development of new technologies and require economic stability. Realizing UN SDGs through continuous technology development may be possible if governments make all stakeholders participate and establish future policies.

2.6 Summary

Several studies have provided evidence-based explanations for the phasing out of conventional fuels and encouraged the development of alternative fuels. However, several barriers lie ahead to sustainable governance, even as the decision-makers have been attempting to identify solutions to maintain sustainability in the maritime industry. Substantial scientific evidence has been provided to justify the use of alternative fuels. For example, fossil fuel combustion is contributing to the acceleration of anthropogenic climate change and contraction of diseases like lung cancer. Therefore, the optimal alternative fuel for the future must be identified and projects to develop technology that can use the fuel while maintaining environmental, economic, and social safety should be initiated.

3. Research Methodology

This study presents the optimal alternative fuel in terms of sustainability. Therefore, it selects both qualitative and quantitative analyses to accomplish the objective. First, LCSA produces results of sustainability. For instance, the environmental goal is calculated by the E-LCA regarding the impact of GHG and acidification. Second, the economic aspect addresses the LCC and NPV. Finally, because the social goal is related to the positive impact of reducing air pollutants, the study uses the S-LCA. In addition, the literature review presents the environmental, social, and economic perspectives of sustainable alternatives. In conclusion, MADM combines the LCSA and literature review to rank and select the optimal alternative fuel among LNG, hydrogen, ammonia, and methanol.

3.1 Life-cycle Sustainability Assessment (LCSA)

The concept of a life-cycle approach to the environment, economic, and social dimensions of sustainability was introduced by Projektgruppe ökologische Wirtschaft

(1987). In addition, according to Keeble (1988), “Sustainable development is, in essence, development that meets the needs and aspirations of the present generation without destroying the resources needed for future generations to meet their needs.” Over the years, the LCA has been developed to address bioenergy. It has been widened and subdivided by the three main pillars of sustainability. Therefore, LCSA (Table 3), a more comprehensive assessment method, has emerged from the LCA’s development. In other words, LCSA is the combination of E-LCA, LCC, and S-LCA (Clift & Druckman, 2015).

Table 3

Criteria of LCSA indicators for the energy sector included in the MADM

Sustainability	LCSA	Criterion	Unit
Environmental	E-LCA	GHG impacts	kgCO_2eq/kWh
		Acidification Potential (AP)	kg SO_2eq/kWh
Economic	LCC	Life-cycle Costs	US$
		Net Present Value (NPV)	US$
Social	S-LCA	Photochemical Oxide Creation Potential (POCP)	kg C_2H_4eq/kWh
		Human Toxicity Potential (HTP)	kg 1,4-DCB [a] eq/kWh

[a] 1,4-Dichlorobenzene ($C_6H_4Cl_2$)

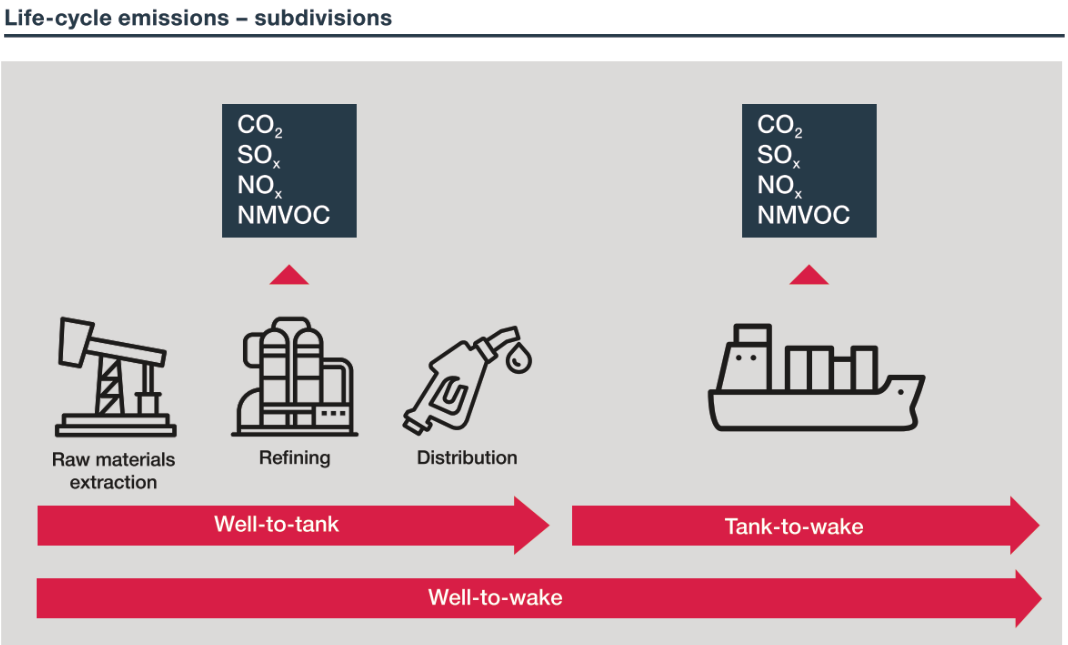
Note. Developed by Author (2022).

3.1.1 Environmental Life-cycle Assessment (E-LCA)

ISO 14040:2006, Environmental Management—E-LCA— Requirements and Guidelines states the general methodology of the E-LCA. The principles and frameworks of E-LCA specified in ISO 14040:2006, Environmental Management, establishes the framework of LCA for quantifying the environmental impact of products, processes, and services in the supply chain. Based on the above, a specific E-LCA methodology can be adopted and applied to marine fuels. In other words, E-LCA is a technique of quantifying the material and energy inputs and outputs of all unit processes that constitute the product system under study to assess the potential environmental impact of a product, system, or service over its entire life cycle, from raw material origin to end of life (Schuller et al., 2019).

Figure 4

Life-cycle emissions—subdivisions



Note. Adopted from “Methanol in shipping, n.d.,” by MAN Energy Solutions, n.d., 2022.

As illustrated in Figure 4, the emission profile of shipping fuels can be subdivided into WtW, well-to-tank (WtT), and tank-to-wake (TtW) emissions (MAN Energy Solution, n.d.). The WtW method can be used to evaluate fuel paths based on the overall life-cycle analysis evaluation and report all relevant GHG emissions following the IPCC guidelines (IMO, 2022). Therefore, this study focuses on WtW to rigorously evaluate the use of alternative fuels.

- **Global Warming Potential 100**

In the E-LCA, WtW is compared to GWP-100, which was developed to compare the effects of global warming on other gases. This study cites the IMO (2022) for the GWP-100 values. The study does not include the scope of cargo emissions (e.g., VOC or refrigerants) because the IMO (2022) does not consider the entire list of GHGs for international maritime transport. Other short-lived climate factors and precursors, such as non-methane VOC, SOx, CO, PM, and black carbon, were not included in the scope for the GWP-100 values. Therefore, GWP-100 deals with CO_2, CH_4, and N_2O, as stated in the IPCC's Sixth Assessment Report.

According to International Council on Clean Transportation (2021), E-LCA is calculated as follows:

- Equation 1.

$$CEF_{WtT} = \Sigma(EF_{WtTp} \times GWP_p\ 100),$$

where

CEF_{WtT} = Well-to-tank carbon dioxide equivalent factor, in kgCO_2eq/kWh;

EF_{WtTp} = Well-to-tank emission factor of pollutant p, in kg/kWh; and

$GWP_p\ 100$ = 100-years GWP of pollutant p.

- Equation 2.

$$CEF_{TtW} = \Sigma(EF_{TtWp} \times GWP_p\ 100),$$

where

CEF_{TtW} = Tank-to-wake CO_2 equivalent factor, in kgCO_2eq/kWh;

EF_{TtWp} = Tank-to-wake emission factor of pollutant p, in kg/kWh; and

$GWP_p\ 100$ = 100-years GWP of pollutant p.

- Equation 3.

$$CEF_{WtW} = CEF_{WtT} + CEF_{TtW},$$

where

CEF_{WtW} =Well-to-wake CO_2 equivalent factor, in kgCO_2eq/kWh;

CEF_{WtT} = Well-to-tank CO_2 equivalent factor, in kgCO_2eq/kWh; and

CEF_{TtW} = Tank-to-wake CO_2 equivalent factor, in kgCO_2eq/kWh.

- **Acidification Potential (AP)**

The acidification caused by SOx and NOx damages marine life. For example, the higher the acidity of the ocean, the faster the $CaCO_3$ shells and skeletons of life forms melt. Accordingly, acidification potential (AP) must be considered an indicator of E-LCA. The AP calculations were based on SO_2. This model was referenced by the EPA's report and is expressed as follows (EPA, 2000 & Li, 2012):

$$AP_i = E_i \times CF_{SO_2},$$

where

AP_i = acidification potential;

E_i = emissions caused by alternative fuels; and

CF_{SO_2} = characterization factors of SO_2.

3.1.2 Life-cycle Cost (LCC)

The LCC is an economic indicator in the LCSA to deal with the economic aspect. It is used in the production and trading of bioenergy in an economical and financially viable manner (Stamford, 2019). Historically, it was by the US Department of Defense in the mid-1960s. In the mid-1980s, it was utilized in building investments. Since the early 2000s, several research projects have utilized it in the construction industry in the environmental context (Gluch & Baumann, 2004).

Recently, attempts to separate energy generation from GHG emissions have gained momentum, leading to tremendous industrial activity. In 2017, the total global investment in low-carbon power generation was $315 billion, while energy efficiency initiatives were $23.6 billion (Stamford, 2019). Therefore, economic factors must be considered while selecting the optimal alternative fuel. Hence, the LCC is one of the methods selected to address the objectives of this study.

The LCC of a product or process is the aggregate of all economic costs directly caused by actors in the life cycle (Stamford, 2019). Hence, it can be defined according to the life-cycle stages essential for an energy-generating asset or piece of technology. According to Wang et al. (2021), the formulation for LCC is as follows:

$$\Sigma LCC_o = \sum_{i=1}^{nCi} C_{ci} + \sum_{i=ni+1}^{nOi} C_{Oi} + \sum_{i=nOi+1}^{nVi} C_{Vi} + \sum_{i=nVi+1}^{nELi} C_{ELi}\ ,$$

where

LCC_o = life-cycle cost of the ship in its lifetime;

C_{ci} = total capital investment costs of the ship in its lifetime;

C_{Oi} = total operating costs of the ship in its lifetime;

C_{Vi} = total voyage costs of the ship in its lifetime; and

C_{ELi} = total end life costs of the ship in its lifetime.

The differences in cash flow performances among the corresponding ships can be estimated by comparing the LCC results of the alternative fuels, as follows (Femando, 2022):

$$NPV = \sum_{t=o}^{n} \frac{R_t}{(1+i)^t}\ ,$$

where

NPV = net present value of LCC;

R_t = net cash inflow–outflow during a single period *t*;

i = discount rate or return that could be earned in alternative investments; and

t = number of time periods.

Based on the formula mentioned above, LCC and NPV, this paper gives the value of LCC and NPV to each alternative fuel option for dealing with the economic perspective of sustainability.

3.1.3 Social Life-cycle Assessment (S-LCA)

S-LCA is a new methodology that shares a lifecycle perspective with the E-LCA to evaluate the entire life cycle of a product; for example, raw material extraction and processing, manufacture, distribution, use, reuse, maintenance, recycling, and final disposal (Ekener et al., 2018). S-LCA largely follows the UN Environment Programme (UNEP) guidelines for linking E-LCA and LCC. However, it is the weakest among the LCSA methodologies. Therefore, S-LCA faces challenges because it is encumbered by environmental and economic assessments (Stamford, 2019). This study addresses two issues related to this demerit.

- **Photochemical oxide creation (POCP)**

Photochemical smog consists of CH_4, SOx, NOx, and VOC. Therefore, POCP is used for assessing the impacts of photochemical smog. Li (2012) stated that the quantity of photochemical smog made by the C_2H_4 and POCP is calculated in the equation below:

$$POCP_i = E_i \times CF_{C_2H_4} ,$$

where

$POCP_i$ = photochemical oxide creation potential;

E_i = emissions caused by alternative fuels; and

$CF_{C_2H_4}$ = characterization factors of C_2H_4.

- **Human Toxicity Potential (HTP)**

The HTP calculation was based on 1,4-dichlorobenzene (Yan, 2005). According to several literature data, the common toxins are comprised of SOx, NOx, CO, and PM10. Therefore, the HTP of the alternative fuels WtW life cycle can be described as follows in the equation below:

$$HTP_i = E_i \times CF_{1,4-C_6H_4Cl_2},$$

where

HTP_i = human toxicity potential;

E_i = emissions caused by alternative fuels; and

$CF_{1,4-C_6H_4Cl_2}$ = characterization factors of 1,4-$C_6H_4Cl_2$.

3.2 Multi-Attribute Decision Making (MADM)

Operations research (OR) is a method that simplifies the human decision-making process. Particularly, multi-criteria decision making (MCDM) has contributed to OR (Zavadskas et al., 2014). MCDM can be divided into two categories: discrete MADM and continuous multi-objective decision making (MODM) (Zavadskas et al., 2014). The discrete MADM method addresses discrete and predetermined alternatives by establishing a multi-criteria table. The main challenges of MADM are the rational choice from limited alternatives and their evaluation and ranking (Zavadskas et al., 2014).

To summarize, Michaels (1989) is quoted: “MADM refers to making preference decisions by evaluating and prioritizing a limited set of alternatives based on multiple conflict attributes.”

MADM uses both qualitative and quantitative attributes to evaluate the characteristics of each alternative:

1) Qualitative attributes

- Identify alternatives and their attributes through academic and industrial literature for systematic and consistent evaluation of alternative maritime fuels.

- Establish multiple criteria through multi-stakeholder participation.

2) Quantitative attributes

- The optimal alternative fuel energy can be inferred from a comparison of collected data.

Therefore, to select the optimal alternative fuels, this study uses TOPSIS using the ideal solution similarity among several methods according to MADM. Hwang and Yoon (1981) developed TOPSIS, the principle of which states that the selected alternative should have the shortest distance from the positive-ideal solution and the longest distance from the negative-ideal solution.

According to Rao (2007), the main steps of the TOPSIS method for selecting the optimal alternative fuel are:

Step 1: Determine the objective and identify the pertinent evaluation attributes.

Step 2: Represent a matrix based on all the information available on attributes.

Step 3: Obtain the normalized decision matrix, R_{ij}.

$$R_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \ i = 1,2,\ldots,M; \ j = 1,2,\ldots,N,$$

where

x_{ij} = value of alternative i concerning attribute j.

Step 4: Decide on the weights of different attributes to the objective.

Step 5: Obtain the weighted normalized matrix V_{ij} .

$$V_{ij} = w_j R_{ij}\ , \ \ i = 1,2,\ldots,M;\ j = 1,2,\ldots,N,$$

where

w_j = weight of the j th attribute.

Step 6: Obtain the positive idea (best) and negative idea (worst) solutions.

$$V^{+} = \left\{ \left(\sum_{i}^{max} V_{ij} /j \in J \right),\ \left(\sum_{i}^{min} V_{ij}/j \in J' \right) /i = 1, 2, \ldots, N \right\} = \{V_1^{+}, V_2^{+}, V_3^{+}, \ldots, V_M^{+}\},$$

$$V^{-} = \left\{ \left(\sum_{i}^{min} V_{ij} /j \in J \right),\ \left(\sum_{i}^{max} V_{ij}/j \in J' \right) /i = 1, 2, \ldots, N \right\} = \{V_1^{-}, V_2^{-}, V_3^{-}, \ldots, V_M^{-}\},$$

where

J = (j = 1,2, ..., M)/ j is associated with beneficial attributes, and

J' = (j = 1,2, ..., M)/ j is associated with non-beneficial attributes.

Step 7: Obtain the separation measures.

$$S_i^{+} = \{\textstyle\sum_{J=1}^{M} (V_{ij} - V_j^{+})^2\}^{0.5},\ i = 1, 2, \ldots, N,$$

$$S_i^{-} = \{\textstyle\sum_{J=1}^{M} (V_{ij} - V_j^{-})^2\}^{0.5},\ i = 1, 2, \ldots, N.$$

Step 8: Relative closeness of a specific alternative to the ideal solution, P_i , can be expressed in this step as follows:

$$P_i = S_i^{-} / (S_i^{+} + S_i^{-})$$

Step 9: Generate a series of alternatives in descending order, depending on the value of P_i representing the most and least preferred feasible solutions. P_i can also be considered an alternative A_i's overall or composite performance score.

4. Evaluation of Alternative Fuel Options based on LCSA

Before analyzing LCSA, the fuel options must be specified in a fuel life-cycle label (FLL), which categorizes the fuel per feedstock, production pathway, and other sustainability aspects.

Table 4

Fuel life-cycle labels (FLLs) for alternatives

Part I [a]		Part II [b]		Part III [c]	Part IV [d]
Carbon content	C_f [e]	Feedstock nature	S_F [f]	Production pathway	Fuel type
Carbonized	Actual carbon content	Natural Gas (NG)	1	NG to LNG Plant	LNG/Methane
Decarbonized	0	NG	N/A	NG combusted in SMR [g] with CO_2 sequestration	Hydrogen
Decarbonized	0	NG	N/A	Ammonia as a Final Fertilizer	Ammonia
Carbonized	Actual carbon content	NG	1	NG to DME/FTD [h] Plant	Methanol

[a] Carbon content of the fuel

[b] [Feedstock Nature] [Primary energy source for production]

[c] Production pathway

[d] Fuel type

[e] Carbon emission factor

[f] Carbon source factor

[g] Steam methane reforming

[h] Dimethyl ether / Fischer–Tropsch diesel

Note. Developed by Author (2022) using data from IMO (2022).

As presented in Table 4, NG has been assumed as the feedstock of all alternative fuel options. The reason for selecting NG is that NG is today's dominant energy source for producing alternative fuels. Table 5 shows the energy converters to which the alternative fuel option will be applied to calculate tank-to-wake emissions.

Table 5

Energy converter for alternative fuel options

	Type of Fuel			
	LNG/Methane	Hydrogen	Ammonia	Methanol
Energy	Internal Combustion Engine (ICE)			
Converter	Solid Oxide Fuel Cells (SOFC)			

Note. Developed by Author (2022).

ICE has been a dominant technology for operating transportation. Typically, commercial vessels use two-stroke internal combustion engines (ICE) for the main propulsion system. It is a mechanical and chemical device that converts the chemical energy of a fuel into mechanical energy and is generally used on a rotating shaft (Fernández-Ríos et al., 2022). ICE typically uses fossil fuels which has caused severe climate catastrophes and air pollution. However, ICE is compatible with alternative fuels (Hansson et al., 2020 & Fernández-Ríos et al., 2022). Therefore, this study selects ICE as the energy converter because existing studies have demonstrated that ICE with alternative fuels is a sustainable technology.

A fuel cell is a promising technology to provide energy for operating transportation. It generates electricity and heat during the electrochemical reaction in which hydrogen reacts with oxygen forming water (Mekhilef et al., 2012). Mekhilef et al. (2012) stated that the adoption of fuel cells depends on operating temperature, efficiency, application, and cost. Fuel cell systems are of six main groups based on the choice of fuel and electrolyte: alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), solid oxide fuel cell (SOFC), molten carbonate fuel cell (MCFC), proton-exchange membrane fuel cell (PEMFC), and direct methanol fuel cell (DMFC). Among these types of fuel cells, the author selected SOFC based on Table 6.

Table 6

Summary of fuel tolerance for different fuel cell types

Type of Fuel Cell	Sulfur	Carbon Monoxide	Ammonia
PEMFC	<0.1 ppm	<100 [a] ppm	Poison
PAFC	<50 ppm	<0.5 %	<4 %
MCFC	<10 ppm	Fuel	<1 %
SOFC	<2 ppm	Fuel	<0.5 %

[a] Standard Pt anode catalysts can only withstand CO concentrations up to 10 ppm, and PtRu alloys up to 30 ppm. These limits can be extended by bleeding air into the anode and using alternative bi-layer catalysts.

Note. Adopted from “The role of hydrogen and fuel cells in the global energy system” by Staffell et al., 2019.

Table 6 shows that all fuel cell systems have constraints regarding input purity to preserve cell life. Furthermore, the ISO 14687-2 standard for transportation PEMFCs requires 99.97 % hydrogen purity (Staffell et al., 2019). Because this study deals with alternative fuels produced from NG, SOFC, which was the most suitable for this study, was selected as another energy converter.

4.1 Analysis of LCSA of Alternative Fuel Options with MADM

4.1.1 E-LCA

- **Global Warming Potential 100**

The author calculated well-to-wake emissions for ICE based on the GREET values and values from the literature for E-LCA. Furthermore, this study utilized the cited peer-reviewed literature to obtain GWP-100 for alternative fueled-SOFCs (WtW) by comparing existing studies. The study used values from the literature for all alternative fuels produced by steam methane reforming. Therefore, the author assumed ICE and SOFC have the same emission values in the well-to-tank cycle.

E-LCA utilizes WtW CO_2eq emissions from GWP-100 by calculating WtT and TtW as follows:

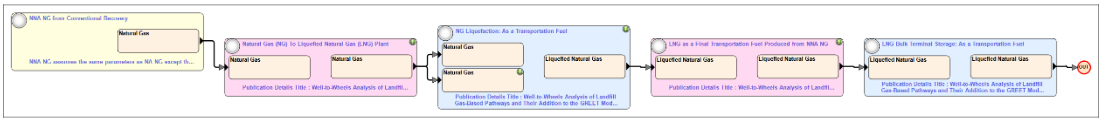
1) Well-to-Tank (WtT)

WtT emissions deal with pollutants during the fuel or energy vectors' production, processing, and delivery. WtT emissions are presented using emission factors from the GREET model and energy content assumptions from the IEA.

- **LNG**

Figure 5

LNG extraction and production



Note. Adopted from "Liquefied Natural Gas (As a Transportation Fuel) from Non-North American Natural Gas, 2020" by GREET, 2020.

WtT for LNG follows "Liquefied Natural Gas (As a Transportation Fuel) from Non-North American Natural Gas" on GREET because shale gas recovery had to be excluded from the data regarding the extraction and production of LNG by non-North American regions. Although shale gas has the same composition as NG, the location of the reservoir is different. NG can be found in large quantities, while shale gas is trapped in fine cracks in the rock, making its extraction difficult. Therefore, the extraction process differs between gases, and air pollutants and GHG emissions also show different levels in the WtT process.

Table 7

Emission factors of LNG (WtT)

	LNG	
Energy content (Lower heating value (LHV))	13.333 kWh/kg	
Amount of LNG	0.075 kg/kWh	
Pollutant	emissions / kg LNG	emissions / kWh
CO_2	0.5856 kg	0.04392 kg
CH_4	13.3636 g	0.00100227 kg
N_2O	9.4807 mg	7.11053×10^{-7} kg

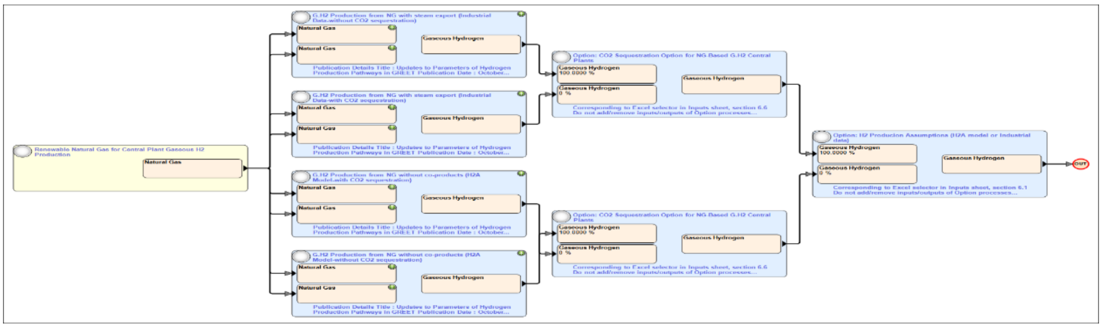
Note. Adapted from "Liquefied Natural Gas (As a Transportation Fuel) from Non-North American Natural Gas" by Mintz et al., 2010. Copyright 2020 by GREET.

LNG's WtT emissions based on data from GREET are provided in Table 7, which refers to GREET and IEA for the energy content (lower heating value (LHV)).

- **Gaseous Hydrogen**

Figure 6

Gaseous hydrogen extraction and production



Note. Adopted from "Compressed G.H2 Produced from Renewable Natural Gas, 2020" by GREET, 2020.

Due to the limitations of WtT data on blue and green-hydrogen, this study uses gray-hydrogen data generated through NG combusted in steam methane reforming (SMR) with CO_2 sequestration to capture CO_2 byproducts in the hydrogen production process.

Hydrogen produced in this process is defined as gray-hydrogen because of the difference between carbon capture and storage (CCS) and CO_2 sequestration. CCS involves capturing, transporting, and storing carbon dioxide. In contrast, CO_2 sequestration refers to only storing carbon dioxide for more extended periods.

Therefore, the author addresses WtT for gaseous hydrogen made using NG without CCS, such as in Figure 6.

Table 8

Emission factors of gaseous hydrogen (WtT)

Gaseous Hydrogen		
Energy content (Lower heating value (LHV))	33.333 kWh/kg	
Amount of Gaseous Hydrogen	0.03 kg/kWh	
Pollutant	emissions / kg $G.H_2$	emissions / kWh
CO_2	−1.2179 kg	−0.036537 kg
CH_4	59.6212 g	0.001788636 kg
N_2O	-1.2979×10^{-4} kg	-3.8937×10^{-6} kg

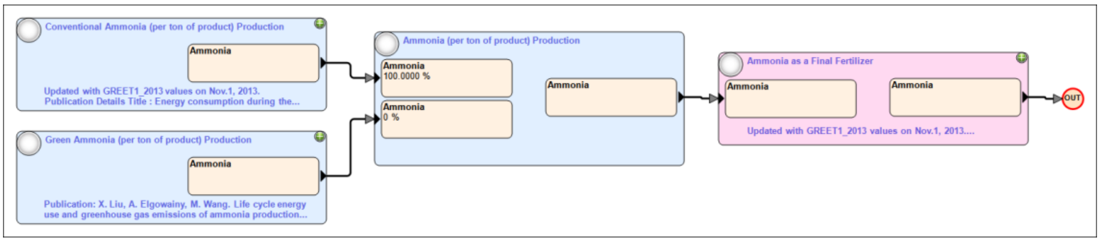
Note. Adopted from “Compressed G.H2 Produced from Renewable Natural Gas” by GREET, 2020. Copyright 2020 by GREET.

Gaseous hydrogen’s WtT emissions based on data from GREET are presented in Table 8, which follows GREET and IEA for the energy content (lower heating value (LHV)).

- **Ammonia**

Figure 7

Ammonia extraction and production



Note. Adopted from “Ammonia Production, 2020” by GREET, 2020.

This thesis selects gray-ammonia produced from NG (Figure 7) to meet the comparison criteria of extraction and production for alternatives like gaseous hydrogen.

Table 9

Emission factors of ammonia (WtT)

Ammonia		
Energy content (Lower heating value (LHV))	5.166 kWh/kg	
Amount of Ammonia	0.1935 kg/kWh	
Pollutant	emissions / kg NH_3	emissions / kWh
CO_2	2.3782 kg	0.460296 kg
CH_4	7.3315 g	0.001419 kg
N_2O	49.3252 mg	9.54681×10^{-6} kg

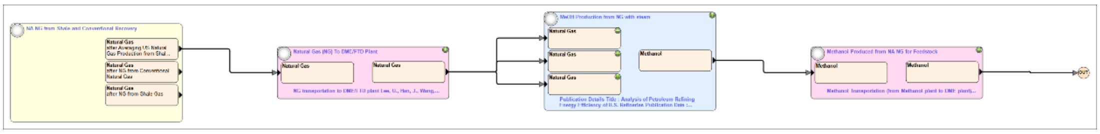
Note. Adopted from "Ammonia Production" by GREET, 2020.

Ammonia's WtT emissions are presented in Table 9 by adopting data from GREET and IEA for the energy content (lower heating value (LHV)).

- **Methanol**

Figure 8

Methanol extraction and production



Note. Adopted from "NG to Methanol for Feedstock, 2020" by GREET, 2020.

In the case of methanol, although data of NG from non-North American regions is preferred to exclude shale gas recovery, this thesis uses emissions factors of methanol made by NG from North America because of limited data on the former. Methanol's WtT emissions are presented in Table 10 based on data from GREET and IEA for the energy content (lower heating value (LHV)).

Table 10

Emission factors of methanol (WtT)

Methanol		
Energy content (Lower heating value (LHV))	5.5278 kWh/kg	
Amount of Methanol	0.1809 kg/kWh	
Pollutant	emissions / kg MeOH	emissions / kWh
CO_2	0.3555 kg	0.064312 kg
CH_4	4.1267 g	0.000746 kg
N_2O	6.5470 mg	1.1844×10^{-6} kg

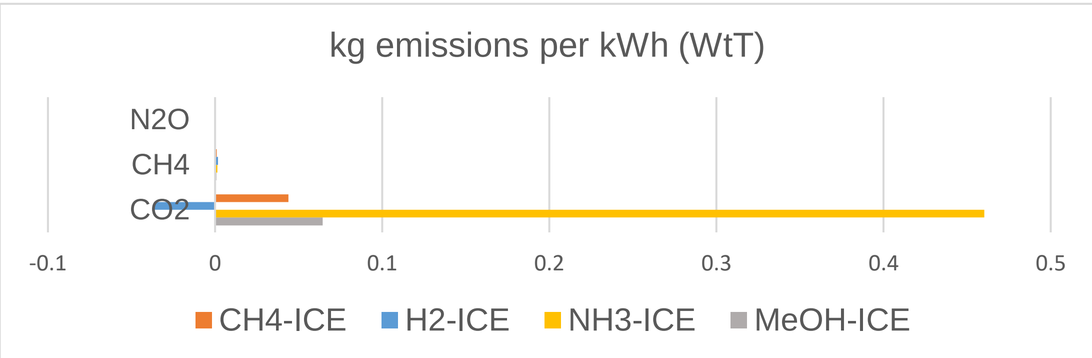
Note. Adopted from "Methanol Production" by GREET, 2020. Copyright 2020 by GREET.

- **Summary**

The WtT calculations for each of the above fuel options are summarized in Figure 9. Further, according to the subsequent tables and figures, the worst-case scenario is the use of ammonia as a marine fuel in terms of WtT.

Figure 9

Graph of calculation of WtT emissions



Note. Developed by Author (2022) based on GREET.

The WtT for all these alternatives was calculated from equation 1 of E-LCA: $CEF_{WtT} = \Sigma(EF_{WtTp} \times GWP_p\ 100)$.

Table 11

GWP for climate pollutants

Pollutant	100-years potential	Source
CO_2	1	Reference level
CH_4	29.8	IPCC AR6 Table 7.15
N_2O	273	IPCC AR6 Table 7.15

Note: Adapted from “Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies.” by ICCT, 2020. Copyright 2020 by ICCT.

Table 12

WtT emissions (kg/kWh of fuel)

Pollutant	LNG	Hydrogen	Ammonia	Methanol
CO_2	0.04392	−0.036537	0.46029677	0.064311558
CH_4	0.00100227	0.001788636	0.001419	0.000746539
N_2O	7.1105×10^{-7}	-3.8937×10^{-6}	9.5468×10^{-6}	1.18438×10^{-6}

Note. Developed by Author (2022).

Table 13

$EF_{WtTp} \times GWP_p$ 100 (kg/kWh of fuel)

Pollutant	LNG	Hydrogen	Ammonia	Methanol
CO_2	0.04392	−0.036537	0.46029677	0.064311558
CH_4	0.02986765	0.053301353	0.0422862	0.022246853
N_2O	0.00019412	−0.00106298	0.00260628	0.000323336

Note. Developed by Author (2022).

Table 14

$\Sigma(EF_{WtTp} \times GWP_p$ 100)

Pollutant	LNG	Hydrogen	Ammonia	Methanol
Total [a]	0.073981763	0.015701373	0.505189254	0.086881747

[a] $kgCO_2eq./kWh$

Note. Developed by Author (2022).

2) Tank-to-Wake (TtW): Internal Combustion Engine (ICE)

The tank-to-wake (TtW) approach considers emissions from combustion or considers the fuel in the tank. This analysis does not consider the fuel production and its transportation to the vessel's tank. Therefore, TtW emissions should be calculated for the ICE and SOFC. The TtW emissions were calculated based on data on combustion emissions from peer-reviewed literature.

- **LNG**

This study utilizes data for two-stroke, slow-speed, and diesel-cycle LNG (LNG–diesel) to calculate TtW for engine combustion (ICE). The emission factors for LNG–Diesel CO_2, CH_4, and N_2O are presented according to the International Council on Clean Transportation (2021) in Table 15.

Table 15

Emission factors of LNG-ICE (TtW)

LNG		
Energy content (Lower heating value (LHV))	13.333 kWh/kg	
Amount of LNG	0.075 kg/kWh	
Pollutant	emissions / kg LNG	emissions / kWh
CO_2	2.75 kg	0.20625 kg
CH_4	0.00148 kg	0.000111 kg
N_2O	0.00022 kg	0.0000165 kg

Note: Adapted from "Tank-to-wake emission factors for each pollutant (EF_{TtW}) and associated carbon dioxide equivalent factors (CEF_{TtW})," by ICCT, 2020. Copyright 2020 by ICCT.

- **Hydrogen**

This thesis refers to the IMO (2022) for data on the emission factors of hydrogen-fueled engine combustion (Table 16).

Table 16

Emission factors of hydrogen-ICE (TtW)

Hydrogen		
Energy content (Lower heating value (LHV))	33.333 kWh/kg	
Amount of G. Hydrogen	0.03 kg/kWh	
Pollutant	emissions / kg G.H_2	emissions / kWh
CO_2	0 kg	0 kg
CH_4	0 kg	0 kg
N_2O	0 [a] kg (TBM [b])	0 [a] kg (TBM [b])

[a] Assumption

[b] Technology Business Management

Note. Adapted from "Development of draft life-cycle GHG and carbon intensity guidelines for maritime fuels (draft LCA guidelines): ISWG-GHG 11/2/3," by IMO, 2022. Copyright 2022 by IMO.

As indicated in Table 16, hydrogen-ICE can be a solution to reach zero carbon emissions.

- **Ammonia**

Table 17 presents the GHG emission factors for ammonia fuel combustion specified by IMO (2022).

Table 17

Emission factors of ammonia-ICE (TtW)

Ammonia		
Energy content (Lower heating value (LHV))	5.166 kWh/kg	
Amount of Ammonia	0.1935 kg/kWh	
Pollutant	emissions / kg NH_3	emissions / kWh
CO_2	0 kg	0 kg
CH_4	0 kg	0 kg
N_2O	0 [a] kg (TBM [b])	0 [a] kg (TBM [b])

[a] Assumption

[b] Technology Business Management

Note. Adapted from “Development of draft life-cycle GHG and carbon intensity guidelines for maritime fuels (draft LCA guidelines): ISWG-GHG 11/2/3,” by IMO, 2022. Copyright 2022 by IMO.

As indicated in Table 17, ammonia-ICE can also be a solution to prevent climate change.

- **Methanol**

Ming and Li (2021) specified the emission factors of methanol as marine fuel for engine combustion, as presented in Table 18.

Table 18

Emission factors of methanol-ICE (TtW)

Methanol		
Energy content (Lower heating value (LHV))	5.5278 kWh/kg	
Amount of Methanol	0.1809 kg/kWh	
Pollutant	emissions / kg MeOH	emissions / kWh
CO_2	2.89 kg	0.523 kg
CH_4	0 kg	0 kg
N_2O	0 kg	0 kg

Note. Adapted from “Methanol as a marine fuel” by Ming & Li, 2021. Copyright 2021 by Nanyang Technological University.

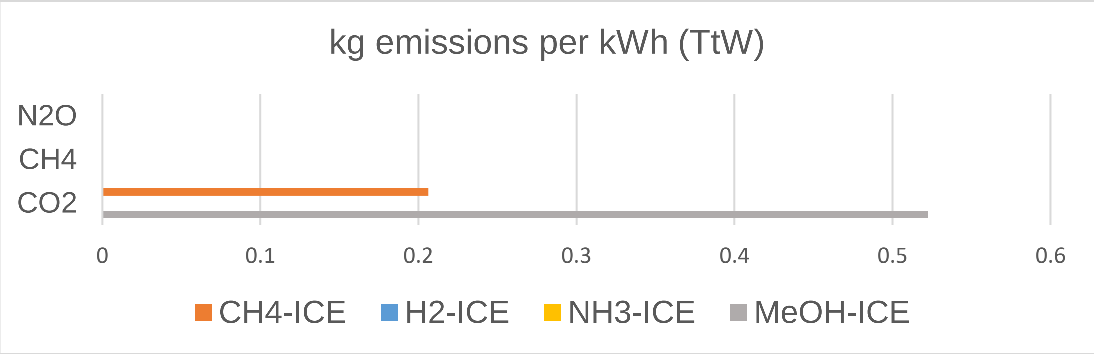
Table 18 shows that the use of methanol-ICE releases CO_2 into the atmosphere, which can cause climate change.

- **Summary**

The TtW calculation for each of the above fuel options are summarized in Figure 10. Moreover, the subsequent tables and figures show that LNG and methanol are not good choices as marine fuels for ICEs, unlike hydrogen and ammonia.

Figure 10

Graph of the calculation of TtW emissions



Note. Developed by Author (2022).

All these alternatives are calculated for TtW according to equation 2 of E-LCA: $CEF_{TtW} = \Sigma(EF_{TtWp} \times GWP_p\ 100)$.

Table 19

TtW emissions (kg/kWh of fuel)

Pollutant	LNG	Hydrogen	Ammonia	Methanol
CO_2	0.20625	0	0	0.52281407
CH_4	0.000111	0	0	0
N_2O	0.0000165	0	0	0

Note. Developed by Author (2022).

Table 20

$EF_{TtWp} \times GWP_p$ 100 (kg/kWh of Fuel)

Pollutant	LNG	Hydrogen	Ammonia	Methanol
CO_2	0.20625	0	0	0.52281407
CH_4	0.0033078	0	0	0
N_2O	0.0045045	0	0	0

Note. Developed by Author (2022).

Table 21

$\Sigma(EF_{TtWp} \times GWP_p\ 100)$

Pollutant	LNG	Hydrogen	Ammonia	Methanol
Total [a]	0.2140623	0	0	0.52281407

[a] $kgCO_2eq./kWh$

Note. Developed by Author (2022).

3) Well-to-Wake (WtW): ICE and SOFC

WtW emissions are the aggregate of WtT and TtW emissions; therefore, WtW is calculated from equation 3 of E-LCA as follows: $CEF_{WtW} = CEF_{WtT} + CEF_{TtW}$ (Table 38).

Table 22

GHG impact (GWP_p 100, $kgCO_2eq./kWh$) of ICE

Alternatives	Well-to-Tank	Tank-to-Wake	Well-to-Wake
CH_4-ICE	0.073981763	0.2140623	0.288044063
H_2-ICE	0.015701373	0	0.015701373
NH_3-ICE	0.505189254	0	0.505189254
MeOH-ICE	0.086881747	0.52281407	0.609695817

Note. Developed by Author (2022).

For assessing GHG impacts on the WtW cycle by SOFC, the author obtained the values of GWP-100 from the cited peer-reviewed literature. The author considered the emission values from the research literature of alternative fuels produced as byproducts of methane reforming by decomposing NG. Therefore, this study assumes that the values of the WtT process obtained from the research literature are the same as the emission values of the WtT cycle used herein. Table 23 compares the results of GWP-100 obtained from the literature.

Table 23

GHG impact (GWP_p 100, $kgCO_2eq./kWh$) of SOFC

Reference	GWP-100 ($kgCO_2eq./kWh$)	Alternatives
Bicer & Khalid, 2020	0.41	CH_4 [a] -SOFC
Bicer & Khalid, 2020 Strazza et al., 2010	0.64 0.51	H_2 [b] -SOFC
Bicer & Khalid, 2020	0.16	NH_3 [c] -SOFC
Bicer & Khalid, 2020 Strazza et al., 2010	0.71 0.99	MeOH [d] -SOFC

[a] References represent CH_4 as NG, but this study represented that CH_4 as LNG because the GHG and air pollutant emissions of NG and LNG are similar, based on the WtT cycle data calculated by GREET.

[b] Produced by steam methane reforming

[c] Produced from fossil fuel-based hydrogen

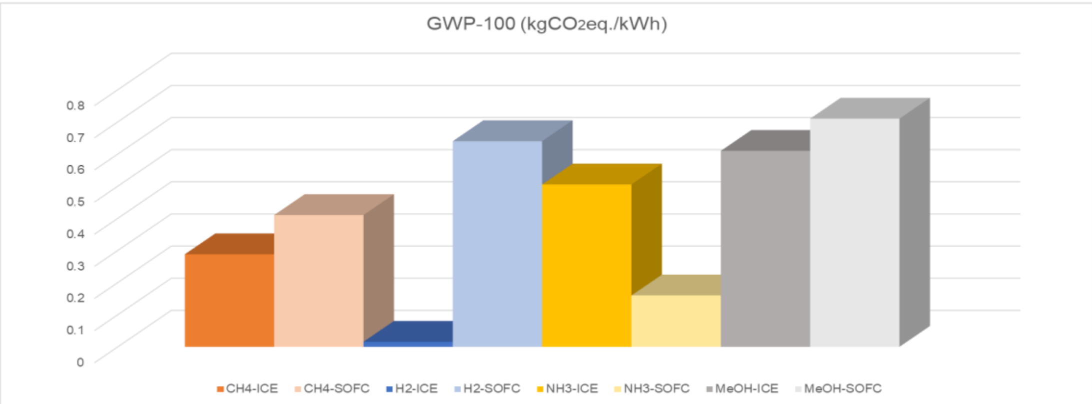
[d] Produced by steam methane reforming and methanol synthesis reaction

Note. Developed by Author (2022) by adopting Bicer & Khalid (2020) and Strazza et al. (2010).

This study considered the recent literature data for the different values listed in Table 23.

Figure 11

GWP-100 graph of the calculation of well-to-wake (WtW) emissions



Note. Developed by Author (2022).

According to Figure 11, GWP-100 proves hydrogen-ICE (0.015701373 kgCO2eq./kWh) to be the optimal alternative from the environmental perspective.

- **Acidification Potential (AP)**

According to the formula of AP based on Chapter 3.1.1, Table 24 demonstrates the AP of the alternative fuel-ICEs' WtW life cycle.

Table 24

AP of the alternative fuel-ICEs' WtW life cycle

LNG-ICE			
Acidic gas	CF [a] (kg SO_2eq)	Emission (kg/kWh)	AP (kg SO_2eq/kWh)
SOx	1	0.0001174	0.00011740
NOx	0.7	0.0013225	0.00092575
Total	—	—	0.00104315
Hydrogen-ICE			
Acidic gas	CF (kg SO_2eq)	Emission (kg/kWh)	AP (kg SO_2eq/kWh)
SOx	1	-7.5×10^{-6}	-7.5×10^{-6}
NOx	0.7	2.6×10^{-3}	0.00187908
Total	—	—	0.00187157
Ammonia-ICE			
Acidic gas	CF (kg SO_2eq)	Emission (kg/kWh)	AP (kg SO_2eq/kWh)
SOx	1	1.43×10^{-4}	1.43×10^{-4}
NOx	0.7	0.0161003	0.0112702
Total	—	—	0.0114135
Methanol-ICE			
Acidic gas	CF (kg SO_2eq)	Emission (kg/kWh)	AP (kg SO_2eq/kWh)
SOx	1	5.96×10^{-5}	5.96×10^{-5}
NOx	0.7	7.54×10^{-3}	0.0052782
Total	—	—	0.0053378

[a] Characterized factor

Note. Developed by Author (2022) by adopting data from GREET and Li (2012).

For AP of the alternative fuel-SOFCs, this paper utilizes values from literature. Table 25 lists the AP from the literature.

Table 25

AP of the alternative fuel-SOFCs' WtW life cycle

Reference	AP (kg SO_2eq./kWh)	Alternatives
Bicer & Khalid, 2020	0.000363	CH_4-SOFC
Bicer & Khalid, 2020	0.001510	H_2 [a] -SOFC
Strazza et al., 2010	0.001510	
Hansson et al., 2020	0.00	NH_3 [b] -SOFC
Bicer & Khalid, 2020	0.000946	MeOH [c] -SOFC

[a] Produced by steam methane reforming

[b] Produced from fossil fuel-based hydrogen

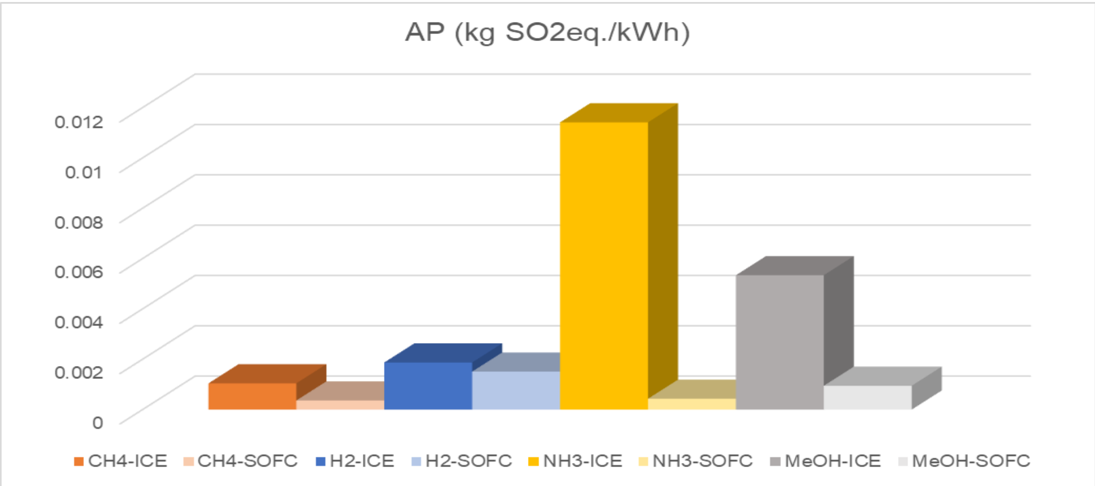
[c] Produced by steam methane reforming and methanol synthesis reaction

Note. Developed by Author (2022) by adopting Hansson et al. (2020), Bicer & Khalid (2020) and Strazza et al. (2010).

Even though Hansson et al. (2020) assumed AP of NH_3-SOFC as 0.00 mole H+ eq./MJ fuel due to the limitation of data, the author considered the value of 0.000431 kg SO_2eq./kWh based on data from GREET and Hansson et al. (2020).

Figure 12

AP graph of the calculation of well-to-wake (WtW) emissions



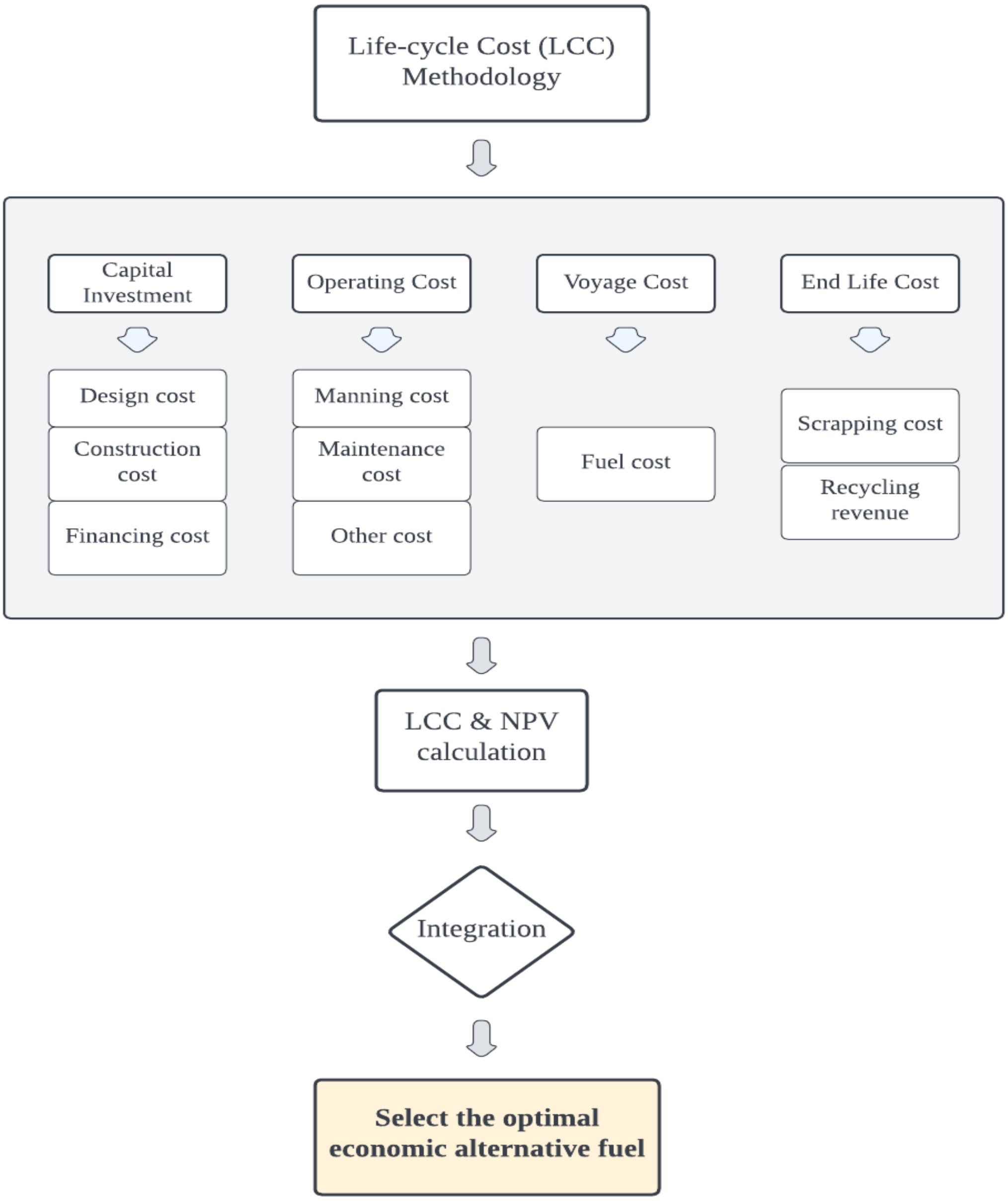
Note. Developed by Author (2022).

As illustrated in Figure 12, NH_3-ICE has the highest total AP among the eight alternatives. The lowest total AP is for CH_4-SOFC.

4.1.2 LCC & NPV

Figure 13

Flowchart of the LCC methodology



Note. Developed by Author (2022).

The research object of this study for LCC and NPV calculations is a Neo-Panamax Containership of 8,000–9,000 TEU. Figure 13 shows the process of selecting the optimal alternative fuel in economic terms using the formulas of LCC and NPV presented in Chapter 3.1.2. Furthermore, the author makes the following assumptions referring to Wang et al. (2021).

a. The comparison between alternative fuel-powered vessels shall be based on the operating parameters, working hours, and average working speed required.

b. The lifetime t of the vessel analyzed in the LCC model is 20 years, with no more operation beyond its lifetime. The ship directly proceeds to the scrapping process.

c. In this feasibility study, the average working speed of the ship is 20 knots, i.e., a 70-days round trip, 55 days at sea, and 15 days at port. The vessel will complete five round trips a year with a total of 350 working days.

d. The structural design and power systems installed in the alternative fuel-powered vessels are the same as the reference line equivalents to the existing fuel vessel.

e. Alternative fuel-powered ships are designed to complete the entire round trip without the need for refueling at the design speed with an alternative fuel tank.

f. The ships refuel at North American ports for spot fuel prices. Further, the price of fuel benchmarks the average price in 2021. External expenditures, such as the impact of long-term fuel supply contracts on bunker prices and bunker service fees charged by fuel suppliers, are negligible.

g. All alternative fuel-powered ships are considered to have ICE or SOFC. In the case of ICE, the amount of pilot fuel oil consumed by this is 5 % of the energy consumed by the engine based on data provided by the engine manufacturer MAN B&W Engine and several studies. The fuel cell system can use 60 % of the fuel energy, which results in a 50 % reduction in fuel consumption compared to the conventional fuel ICE, according to U.S Department of Energy (2015) and Program (2006).

h. All ships in the feasibility study are directly financed and operated by the shipowner. The impacts of different chart types and financing methods on the capital investment costs and returns are negligible.

i. The LCC performances of alternative fuel-powered ships are determined by the associated life cost and cash flow. The study focuses only on the cost factors considered significantly different among the eight types of ships. The remaining cost factors are the same between the reference and alternative cases. This does not jeopardize the reliability of the results.

j. Seafarers working on these ships are the same as those on the conventional ones.

k. The total life-cycle cost is measured in US$, abbreviated as $.

l. The discount rate is 6 % when referring to market research (Adachi et al., 2014).

m. The capital cost is the same as the cost after depreciation of the vessel and is assumed to be 10 % of the initial cost by the straight-line method for ten years without residual value (Adachi et al., 2014).

n. The initial cost of a Neo-Panamax Containership 8,000–9,000 TEU using IFO is $132 million, according to market research (Clarkson's Shipping Intelligence Network, n.d.).

o. According to the TtW analysis of E-LCA, the shipowner will significantly help avoid the proposed carbon tax ($250 to $450 per t$CO_2$) on diesel by operating alternative fuel-propelled ships. Therefore, the carbon tax is zero.

p. Due to the limitation of data for scrapping cost and recycling revenue of alternative fuel propulsion ship, the scrap cost and recycling revenue of an alternative-fuel-propelled Neo-Panamax Containership is approximately

$19.25 million, based on a $/LDT of 590, as in a conventionally fueled vessel.

The total capital investment cost of the ship throughout its lifetime (C_{ci}) is a summation of the design, construction, and finance costs, such as classification society fees and port charges. Therefore, the capital cost is the sum of the first expenditures on a vessel.

Table 26

Capital cost C_{ci} of a Neo-Panamax Containership 8,000–9,000 TEU

Alternatives	Energy Converter	Initial Cost [a]	Capital Cost [b]	Source
LNG	SOFC	335,406,435	33,540,643	Wang et al., 2021 Adachi et al., 2014
	ICE	233,398,200	23,339,820	Taljegard et al., 2014
Hydrogen	SOFC	358,062,609	35,806,261	Hansson et al., 2020 Grahn et al., 2017
	ICE	238,919,652	23,891,965	Taljegard et al., 2014
Ammonia	SOFC	304,274,000	30,427,400	Hansson et al., 2020
	ICE	235,220,200	23,522,020	Taljegard et al., 2014
Methanol	SOFC	330,653,391	33,065,339	Maersk, 2021
	ICE	204,064,000	20,406,400	Taljegard et al., 2014

[a] ($\sum_{i=1}^{nCi} C_{ci}$) in US$

[b] (C_{ci}) in US$

[c] Internal Combustion Engine

Note. Developed by Author (2022).

The total operating cost of the ship throughout its lifetime (C_{Oi}) is the sum of the manning, maintenance, and miscellaneous costs during operation.

Table 27

Operating cost C_{Oi} of the Neo-Panamax Containership

Alternatives	Energy Converter	Operating Cost (C_{Oi}) ($/year)	Source
LNG	SOFC	11,086,000	Wang et al., 2021 Hansson et al., 2020 Adachi et al., 2014
	ICE	9,386,000	
Hydrogen	SOFC	10,686,000	Hansson et al., 2020 Grahn et al., 2017 Adachi et al., 2014
	ICE	10,186,000	
Ammonia	SOFC	9,586,000	Hansson et al., 2020 Adachi et al., 2014
	ICE	10,186,000	
Methanol	SOFC	10,886,000	Maersk, 2021 Adachi et al., 2014
	ICE	9,386,000	

[a] Internal Combustion Engine

Note. Developed by Author (2022).

For the LCC, the fuel cost should be addressed for all alternatives to the voyage cost.

Table 28

Fuel cost C_{Vi} of the containership

Alternatives	Energy Converter	LHV (kWh/kg)	Fuel Consumption [a] (ton/day)	Fuel Price (US$/ton)	Fuel Cost (C_{Vi}) in $/year
VLSFO	ICE	10.83	171.57	861.50 [b]	51,791,767
LNG	SOFC	13.33	66.21	616.50 [b]	15,038,612
	ICE		132.42		31,162,950
Hydrogen	SOFC	33.33	27.87	2,200 [b]	21,459,900
	ICE		55.75		43,370,713
Ammonia	SOFC	5.17	179.70	310 [c]	19,497,450
	ICE		348.62		38,523,595
Methanol	SOFC	5.53	159.60	417 [d]	23,293,620
	ICE		319.20		46,847,466

[a] It is calculated referring to a 49,545-HP 2-stroke engine.

[b] Market research (2021)

[c] Perčić et al. (2022)

[d] Martin, A. (2021)

Note. Developed by Author (2022).

In the shipping industry, when a ship reaches its age limit, ship owners sell them to ship breakers at a negotiable price per lightweight ton. According to Wang et al. (2021), in this study, the end-life cost of a ship is considered to primarily consist of scrap imports. The revenue for the scrap can be expressed as:

$$C_{Scrap} = -k_{scrap} * \triangle_{ltw},$$

where

k_{scrap} = negotiated unit scrap price (USD/lwt);

$\triangle_{ltw}$ = lightweight tonnage of the ship.

Based on Tables 39–41, the results of the LCC are as follows:

Table 29

LCC for alternative fuel options at the end of the 20-year lifetime (from 1 to 4, where 1 indicates the highest ranking)

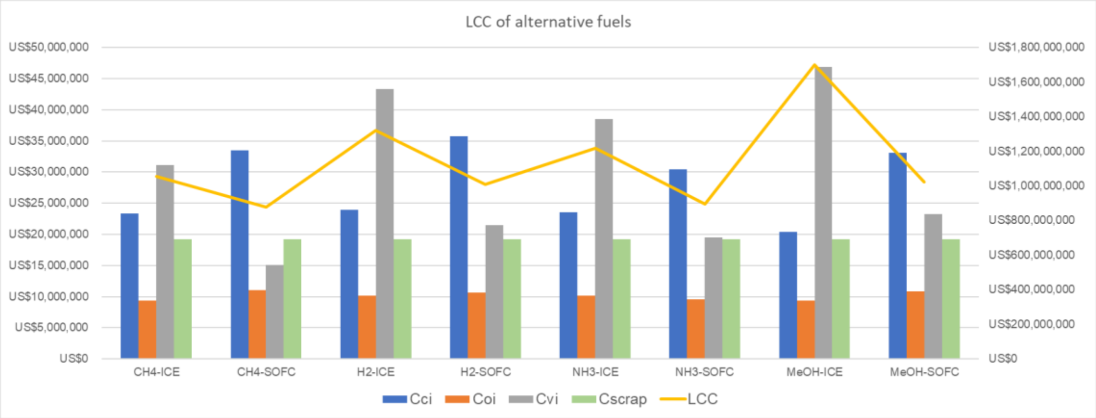
Alternatives	Energy Converter	LCC [a]
LNG	SOFC	877,148,675$
	ICE	1,055,463,207$
Hydrogen	SOFC	1,010,366,609$
	ICE	1,320,739,919$
Ammonia	SOFC	896,129,000$
	ICE	1,218,998,097$
Methanol	SOFC	1,024,431,791$
	ICE	1,699,737,747$

[a] $\sum_{i=1}^{nCi} C_{ci} + \sum_{i=ni+1}^{nOi} C_{Oi} + \sum_{i=nOi+1}^{nVi} C_{Vi} + \sum_{i=nVi+1}^{nELi} C_{ELi}$

Note. Developed by Author (2022).

Figure 14

Graph of LCC of alternative fuel options



Note. Developed by Author (2022).

As indicated in Table 29 and Figure 14, CH_4-SOFC is the most suitable alternative fuel in terms of the LCC. Furthermore, the results of the NPV, which is the amount of all the cash flows discounted to the present using the time value of money, are as follows:

Table 30

NPV of alternative fuels

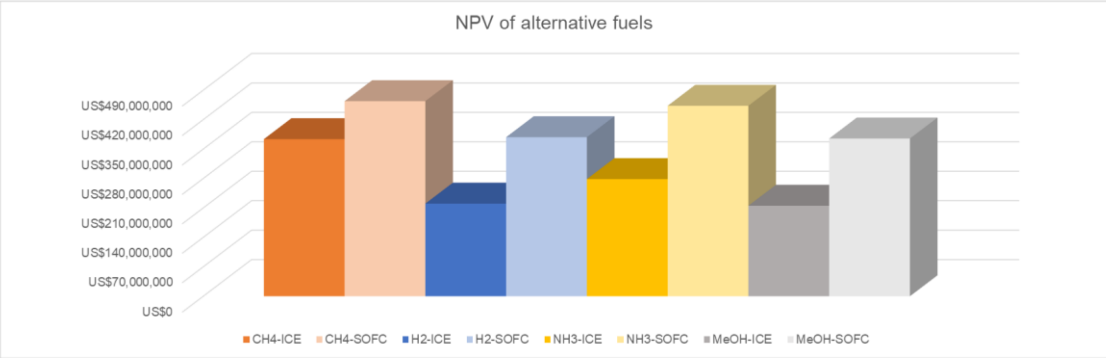
Alternatives	Energy Converter	NPV [a]
LNG	SOFC	463,899,003$
	ICE	373,531,927$
Hydrogen	SOFC	378,160,162$
	ICE	220,270,073$
Ammonia	SOFC	452,875,107$
	ICE	278,588,970$
Methanol	SOFC	375,006,977$
	ICE	215,221,991$

[a] $\sum_{t=o}^{n} \frac{R_t}{(1+i)^t}$

Note. Developed by Author (2022).

Figure 15

Graph of NPV of alternative fuel options



Note. Developed by Author (2022).

Therefore, as per the results of the LCC and NPV, the alternative fuels after CH_4-SOFC ranked in the descending order of economic sustainability are NH_3-SOFC > H_2-SOFC > MeOH-SOFC > LNG-ICE > NH_3-ICE > H_2-ICE > MeOH-ICE.

4.1.3 S-LCA

As mentioned in Chapter 2.3, the IMO & EU have attempted to phase out propulsion systems that emit air pollutants to protect human health and marine life. This chapter assesses social sustainability by addressing each fuel option's POCP and HTP.

As an assumption for the E-LCA, the author assumed NG as the feedstock. Therefore, alternative fuel options for social evaluation are considered the same way as the FLL (Table 4) in the environmental evaluation. Further, this study does not consider a waste-disposal period, as the emitted gas from the ship is not recycled. The collection of data for the fuel-production period is complex, and therefore this period was excluded from the S-LCA. All calculations for POCP and HTP address WtW to address the entire life cycle of alternatives as in the E-LCA.

- **Photochemical Oxide Creation Potential (POCP)**

Photochemical oxide creation (POCP) is an essential indicator of NOx and CH_4 emissions. These compounds react with hydroxyl radicals and generate tropospheric ozone (O_3) in the atmosphere. At the terrestrial level, POCP damages human health, ecosystems, and agricultural yields (Balcombe et al., 2021). Table 31, based on the formula of POCP in Chapter 3.1.3, lists the calculation results of POCP of ICEs.

Table 31

POCP of the alternative fuel-ICEs' WtW life cycle

LNG-ICE			
Photochemical smog gas	CF (kg C_2H_4eq)	Emission (kg/kWh)	POCP (kg C_2H_4eq/kWh)
CH_4	0.006	0.0011002	6.60×10^{-6}
SOx	0.048	0.0001174	5.64×10^{-6}
NOx	0.028	0.0013225	0.00003703
VOC	0.416	0.0001028	4.28×10^{-5}
Total	—	—	9.20×10^{-5}
Hydrogen-ICE			
Photochemical smog gas	CF (kg C_2H_4eq)	Emission (kg/kWh)	POCP (kg C_2H_4eq/kWh)
CH_4	0.006	0.0017886	1.07×10^{-5}
SOx	0.048	-7.51×10^{-6}	-3.60×10^{-7}
NOx	0.028	0.0026844	7.52×10^{-5}
VOC	0.416	-0.000129	-5.37×10^{-5}
Total	—	—	3.19×10^{-5}
Ammonia-ICE			
Photochemical smog gas	CF (kg C_2H_4eq)	Emission (kg/kWh)	POCP (kg C_2H_4eq/kWh)
CH_4	0.006	0.001419	8.51×10^{-6}
SOx	0.048	0.000143	6.88×10^{-6}
NOx	0.028	0.016100	0.0004508
VOC	0.416	0.000991	0.0004126
Total	—	—	0.0008788

Methanol-ICE			
Photochemical smog gas	CF (kg C_2H_4eq)	Emission (kg/kWh)	POCP (kg C_2H_4eq/kWh)
CH_4	0.006	0.0007393	4.43×10^{-6}
SOx	0.048	5.96×10^{-5}	2.86×10^{-6}
NOx	0.028	0.0075402	0.0002111
VOC	0.416	0.0002229	9.27×10^{-5}
Total	—	—	0.0003111

Note. Developed by Author (2022) based on Li (2012).

The results in Table 31 highlight CH_4-SOFC as the best alternative in terms of POCP.

This study uses the literature value for the POCP of alternative fuel-SOFCs. Table 32 summarizes the SOFCs concerning the literature.

Table 32

POCP of the alternative fuel-SOFCs' WtW life cycle

Reference	POCP (kg C_2H_4eq/kWh)	Alternatives
Strazza et al., 2010	0.000028	CH_4-SOFC
Strazza et al., 2010	0.000382	H_2 [a] -SOFC
Bicer & Khalid, 2020	0.000800	NH_3 [b] -SOFC
Strazza et al., 2010	0.000204	MeOH [c] -SOFC

[a] Produced by steam methane reforming

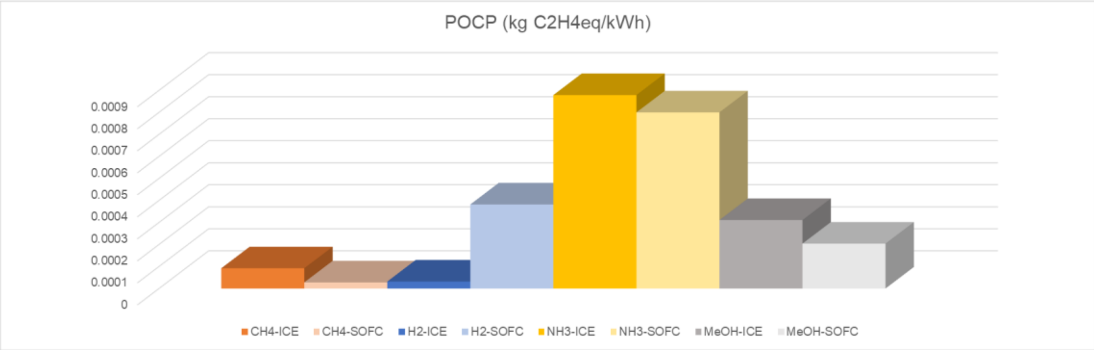
[b] Produced from fossil fuel-based hydrogen

[c] Produced by steam methane reforming and methanol synthesis reaction

Note. Developed by Author (2022) based on Bicer & Khalid (2020) and Strazza et al. (2010).

Figure 16

POCP graph of the calculation of well-to-wake (WtW) emissions



Note. Developed by Author (2022).

As illustrated in Figure 16, NH_3-ICE has the highest total POCP among the eight alternatives. The lowest total POCP is for CH_4-SOFC.

- **Human Toxicity Potential (HTP)**

Alternative fuels can increase human toxicity potential. A study defined HTP as an indicator of the potential harm of a unit of chemical released into the environment based on the toxicity and potential dose of a compound. The HTP weighs emissions listed as part of S-LCA (Hertwich et al., 2001).

Table 33, based on the HTP formula in Chapter 3.1.3, indicates the calculation process of HTP of ICEs.

Table 33

HTPs of the alternative fuel-ICEs' WtW life cycle

LNG-ICE			
HT substance	CF (kg 1,4-$C_6H_4Cl_2$eq)	Emission (kg/kWh)	HTP (kg 1,4-$C_6H_4Cl_2$eq/kWh)
SOx	0.096	0.0001174	1.13×10^{-5}
NOx	1.2	0.0013225	0.001587
CO	0.012	0.0010955	1.31×10^{-5}
PM10	0.82	0.0000116	9.49×10^{-6}

Total	—	—	0.0016209
Hydrogen-ICE			
HT substance	CF (kg 1,4-$C_6H_4Cl_2$eq)	Emission (kg/kWh)	HTP (kg 1,4-$C_6H_4Cl_2$eq/kWh)
SOx	0.096	-7.51×10^{-6}	-7.21×10^{-7}
NOx	1.2	0.0026844	0.0032213
CO	0.012	−0.000195	−0.0000023
PM10	0.82	−0.000018	-1.48×10^{-5}
Total	—	—	0.00320344
Ammonia-ICE			
HT substance	CF (kg 1,4-$C_6H_4Cl_2$eq)	Emission (kg/kWh)	HTP (kg 1,4-$C_6H_4Cl_2$eq/kWh)
SOx	0.096	0.0001433	1.37×10^{-5}
NOx	1.2	0.0161003	0.0193204
CO	0.012	0.0010331	1.24×10^{-5}
PM10	0.82	1.87×10^{-5}	1.54×10^{-5}
Total	—	—	0.0193619
Methanol-ICE			
HT substance	CF (kg 1,4-$C_6H_4Cl_2$eq)	Emission (kg/kWh)	HTP (kg 1,4-$C_6H_4Cl_2$eq/kWh)
SOx	0.096	5.96×10^{-5}	5.73×10^{-6}
NOx	1.2	0.0075402	0.0090483
CO	0.012	0.0003046	3.66×10^{-6}
PM10	0.82	6.81×10^{-6}	5.58×10^{-6}
Total	—	—	0.0090632

Note. Developed by Author (2022) based on Li (2012).

As indicated in Table 33, CH_4-SOFC has the lowest total HTP among the four options.

The author utilizes the literature values for the HTP of alternative fuel-SOFCs. Table 34 lists the values from the literature.

Table 34

HTP of the alternative fuels-SOFCs' WtW life cycle

Reference	HTP (kg 1,4-$C_6H_4Cl_2$eq/kWh)	Alternatives
Bicer & Khalid, 2020	0.005590	CH_4-SOFC
Bicer & Khalid, 2020	0.006140	H_2 [a] -SOFC
Bicer & Khalid, 2020	0.006870	NH_3 [b] -SOFC
Bicer & Khalid, 2020	0.009450	MeOH [c] -SOFC

[a] Produced by steam methane reforming

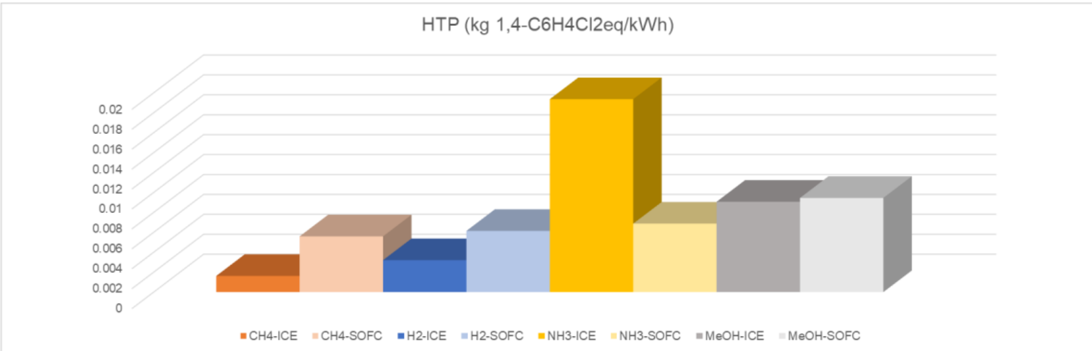
[b] Produced from fossil fuel-based hydrogen

[c] Produced by steam methane reforming and methanol synthesis reaction

Note. Developed by Author (2022) based on Bicer & Khalid (2020).

Figure 17

HTP graph of the calculation of well-to-wake (WtW) emissions



Note. Developed by Author (2022).

As illustrated in Figure 17, NH_3-ICE has the highest total HTP among the eight alternatives. The lowest total HTP is for CH_4-ICE.

4.2 Ranking of Alternative Fuels based on MADM

Table 35

Sustainability rank of alternative options (from 1 to 8, where 1 indicates the highest ranking)

Sustainability		Alternative fuel options			
		CH_4	H_2	NH_3	MeOH
Environmental	GHG	4 (SOFC)	7 (SOFC)	2 (SOFC)	8 (SOFC)
		3 (ICE)	1 (ICE)	5 (ICE)	6 (ICE)
	AP	1(SOFC)	5 (SOFC)	2 (SOFC)	3 (SOFC)
		4 (ICE)	6 (ICE)	8 (ICE)	7 (ICE)
Economic	LCC	1(SOFC)	3 (SOFC)	2 (SOFC)	4 (SOFC)
		5 (ICE)	7 (ICE)	6 (ICE)	8 (ICE)
	NPV	1 (SOFC)	3 (SOFC)	2 (SOFC)	4 (SOFC)
		5 (ICE)	7 (ICE)	6 (ICE)	8 (ICE)
Social	POCP	1 (SOFC)	6 (SOFC)	7 (SOFC)	4 (SOFC)
		3 (ICE)	2 (ICE)	8 (ICE)	5 (ICE)
	HTP	3 (SOFC)	4 (SOFC)	5 (SOFC)	7 (SOFC)
		1 (ICE)	2 (ICE)	8 (ICE)	6 (ICE)

Note. Developed by Author (2022).

Although each option can be ranked according to each criterion, as indicated in Table 35, which summarizes the sustainability ranks of alternative fuel options, all criteria cannot be assumed to possess equal weight, because the significance of each criterion is different. Consequently, selecting weights suitable for each criterion is one of the main steps in MADM. The various methods for selecting weights available in the research literature can be classified into two groups: subjective weights and objective weights (Lotfi & Fallahnejad, 2010).

Subjective weights may be preferred in most real-world problems because of requisitions for considering the decision-maker's expertise and judgment. However, using objective weights is useful when reliable subjective weights are difficult to obtain. Therefore, the author utilizes the Shannon entropy concept, an objective weighting measure, because of limitations in considering the expertise and judgment of all decision-makers. The larger the entropy value of a particular attribute in MADM, the smaller the weight of the attribute, and the less discriminating the attribute in the decision-making process.

4.2.1 Entropy Method

Rao (2007) stated that the entropy method was introduced by Shannon and Weaver (1947) and has been highlighted by Zeleny (1982) for deciding the objective weights of attributes. Furthermore, the entropy method is an indicator to measure the uncertainty of the formulated information using the probability theory (Rao, 2007). Rao (2007) utilized the normalization of the arrays of decision matrix (performance indices) to determine the objective weights as the entropy method as follows:

$$R_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} ,$$

$$e_j = -k \sum_{i=1}^{N} R_{ij} ln R_{ij} ,$$

$$d_j = 1 - e_j ,$$

$$w_j = d_j / \sum_{k=1}^{M} d_k .$$

where

x_{ij} = values of decision matrix;

R_{ij} = the project outcomes;

e_j = entropy value;

k = 1/ln N, which is a constant that guarantees 0 ≤ e_j ≤ 1;

d_j = degree of divergence of the average information contained by each attribute; and

w_j = objective weight for each attribute.

The process of determining the weights by the entropy method using the above formula (Rao, 2007) is described in Appendix 2.

Table 36

Objective weights obtained by the entropy method

	Sustainability					
	E-LCA		LCC		S-LCA	
Attributes	GHG	AP	LCC	NPV	POCP	HTP
Weights (%)	13.47	40.67	0.80	2.44	28.96	13.65
Total (%)	54.15		3.25		42.61	

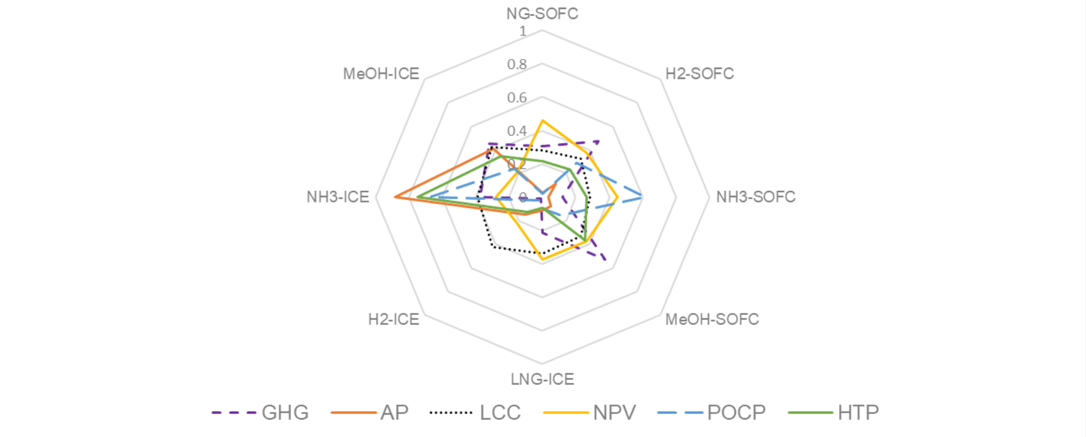
Note. Developed by Author (2022).

The analytical values obtained using the objective weights (Table 36) based on the entropy method are similar to the author's subjective values because the author considers future decisions to significantly depend on additional knowledge regarding social and environmental influences, consequences, and effects.

Figure 18 depicts the alternative fuel's relative performance with different criteria. On the one hand, the lower the values of GHG impact, AP, LCC, POCP, and HTP, the better the performance. On the other hand, the higher the NPV value, the better the performance. Further, none of the options investigated are simultaneously optimal for all criteria.

Figure 18

Octagonal diagram of the relative performance of alternatives with different criteria



Note. Developed by Author (2022).

Table 37

Ranking order of the alternative options (from 1 to 8, where 1 indicates the highest ranking) through the entropy method

Option	CH_4	H_2	NH_3	MeOH
P_i [a]	0.90052 (SOFC)	0.75582 (SOFC)	0.67218 (SOFC)	0.79989 (SOFC)
	0.911036 (ICE)	0.884124 (ICE)	0.047729 (ICE)	0.562420 (ICE)
Rank	2 (SOFC)	5 (SOFC)	6 (SOFC)	4 (SOFC)
	1 (ICE)	3 (ICE)	8 (ICE)	7 (ICE)

[a] Most preferred workable solution score

Note. Developed by Author (2022).

The results in Figure 18 and Table 37 were obtained by applying the weights described in Table 36 to the TOSIS analysis. Hence, according to Appendix 3, Table 37, and Figure 18, through LCSA and MADM, this thesis proved that LNG-ICE is the optimal alternative for sustainability.

5. Discussion

Each result obtained by assessing the environmental, economic, and social sustainability capabilities reveals that no alternative is superior in all criteria. However, the objective evaluation of the capabilities of the sustainability criterion through TOSIS analysis applying the entropy method attributed the highest P_i (most preferred workable solution score) of 0.9110 to LNG-ICE. LNG-SOFC's P_i, ranked second, i.e., 0.9005, which is a difference of only 0.0105 from the P_i of LNG-ICE. In particular, the scores of the first to fifth places differed within a narrow range of 0.15522, indicating that the difference in the P_i of the first to fifth places is marginal. In other words, LNG-ICE & SOFC, H_2-ICE & SOFC, and MeOH-SOFC are all likely to be exceptional alternatives to the existing fuel propulsion technologies.

LNG—the alternative fuel used in the propulsion technology ranked first—has already been technically certified and commercialized. For example, according to SEA-LNG (n.d.), since 2010, the number of ships using LNG fuel has steadily increased between 20 % and 40 % per year. At the beginning of 2020, 175 LNG fuel ships were sailing, and more than 200 LNG propulsion ships were ordered. In addition, 10%–20% of new ship orders are fueled by LNG and are increasingly concentrated on deep-sea vessels such as cruise ships, container ships, crude oil and product tankers, and bulk ships (SEA-LNG, n.d.). DNV (n.d.) also expects 317 LNG propulsion ships to operate in 2028. Because of the technical realization of LNG-fueled propulsion, ports, fuel, and engine infrastructure are already being developed. As shown in Figure 19, the LNG bunkering infrastructure is well-established in the major world sea lanes for container ships, which are the Atlantic route, the Pacific route, and the European–Asian route. Therefore, LNG is the optimal alternative fuel for the available infrastructure of technical sustainability, which refers to the compatibility with the current storage volume, distribution volume, bunkering facilities, and maturity of ship propulsion technology.

Figure 19

LNG bunkering infrastructure in the world

Note. Adopted from "Alternative Fuel Insight: Map" by DNV, n.d.

LNG is an alternative fuel with a well-constructed value chain from extraction to use. However, it has a significant obstacle regarding a reliable fuel supply for technical sustainability. Although a stable supply infrastructure for NG is being developed with its technology development, the availability of raw materials for NG depends on the reserves. The practicality of natural gas use varies significantly depending on the risk of energy security or supply disruptions, affected by the political stability in countries with high supply potential. For example, countries with significant reserves of NG could significantly limit the distribution of LNG by limiting the LNG exports, number of fuels, and currency available at the time of entry. Furthermore, NG is a fossil fuel. If exports are limited due to LNG regulations in countries with high LNG raw material reserves, events such as oil shocks may recur.

In addition, most alternative fuels are produced using NG. Particularly, hydrogen, which is ranked second after LNG, is primarily produced as a byproduct of the decomposition of NG to produce ethanol or as gray-hydrogen produced by

SMR, potentially increasing the prices of NG. Thus, the problem of NG production and supply poses a significant barrier to other alternative fuel options.

Furthermore, low-carbon hydrogen production is in its early stages of commercial development. First, given that its production on a commercial scale is currently minimal, the consumer demand must be continuously monitored. Second, the development of the value chain in hydrogen production, transportation, storage, and distribution is hindered by the absence of a hydrogen-only regulation and policy structure. Finally, due to the lack of physical infrastructure for distribution and storage, hydrogen is considered vulnerable regarding energy security (Pathways, 2021).

However, hydrogen is more likely to fulfil upcoming legislation than the other options. For example, the IEA (2021) stated that policy actions regarding hydrogen and its production have significantly improved in recent years, with governments worldwide adopting hydrogen strategies. These governments are designing plans to implement hydrogen throughout their economies. For example, Germany passed a dedicated bill by updating the Energy Act to provide hydrogen network regulation. In addition, in April 2021, the Australian prime minister pledged A$275.5 million to accelerate the development of hydrogen hubs (Pathways, 2021). In addition, if alternative fuels can be mass-produced using RE obtained through solar or wind energy through policy innovation in each country, this study would produce different results. Notably, hydrogen, ammonia, and methanol can be produced in an environmentally friendly manner using RE resources, reducing the fossil fuel depletion, climate change, and PM impacts of these fuels in SOFC systems. For example, using wind power for hydrogen production can reduce the impact of climate change to 0.05 kgCO_2eq./kWh (Bicer & Khalid, 2020).

6. Conclusion and Recommendations

6.1 Conclusion

Alternative marine fuels are needed to reduce the short- and long-term environmental and climate impacts of shipping. Alternative marine fuels have received increasing attention in recent years, and various options with various characteristics are being considered. In line with this, this study attempted to answer the question: what is the best propulsion technology with alternative fuel in terms of sustainability? To answer this question, this study first conducted an LCSA to evaluate the environment, economy, and social performance of an ICE that generates an output by igniting each alternative fuel for ship propulsion and an SOFC that produces heat and power using alternative fuels.

The LCSA is divided into E-LCA, LCC, and S-LCA. The E-LCA deals with climate change impacts and acidification. In addition, LCC includes the LCC and NPV considering the ship's operation from the ship owner's perspective. Finally, S-LCA considers the adverse health effects by calculating POCP and HTP. This cradle-to-grave life cycle includes extraction of NG raw materials, processing and production of other chemicals, and shipbuilding and decommissioning using alternative fuel propulsion technology. However, the LCSA analysis revealed that the performance of the marine fuel depended on the type of fuel and criterion. For example, some fuels have better environmental or social performance, while others have better economic performance. Thus, comprehensive comparisons were a complex task, and an approach based on multi-criteria decision analysis was needed. Therefore, the results were derived by ranking the integrated sustainability through the MADM methodology. The study results show that using LNG-fed ICE as a propulsion technology yielded lower environmental, economic, and social impacts than the other tested alternatives.

Additionally, this study demonstrates that the application of LCSA to different systems within the same system category can be a helpful decision-making tool for process selection and environmental, economic, and social improvements. In addition, the methodological basis of the analysis consists of the TOPSIS of MADM with the entropy method, which ensures comparability between different studies in the same service group. Hence, the author deems the solution suggested by the LCSA results objective. However, the results of this study were also affected by the selection of evaluation criteria. Imposition of more criteria could change the results to some extent. The impact of fuel ranking will depend on the performance and weight with the new criteria compared to those already included, and the results are unpredictable. The criteria included in this study cover several vital aspects; however, other criteria to clarify the role of alternative fuel options may be required. For example, S-LCA uses uncertainty as an indicator to measure sustainability. This study did not consider several possible indicators, such as media impact, upcoming legislation, local employment, diversity of fuel supply mix, and fuel storage capabilities (energy density) concerning issues related to stakeholders, including workers, consumers, local communities, society, and value chain actors. Therefore, the inclusion of other criteria could further clarify the ranking of alternative fuel options.

In addition, all alternative fuels were extracted from NG and not produced using RE when evaluating the alternative fuel options with LCSA. Although this is the primary method to generate alternative fuel options, the method might change in the future. Further, all market data could not be considered in terms of the cost analysis of the shipping sector; this may have affected the results. However, future cost estimates are always uncertain, and all potential improvements were assumed to be of present value. Recent studies have used various criteria to evaluate alternative fuels' social sustainability. Therefore, the social criteria for valuating alternative fuels are not clear. Despite these research limitations, all alternative fuel options in this study were analyzed through the LCSA with the same evaluation criteria and ranked through TOPSIS analysis of the MADM methodology using the entropy method, an objective weight distribution method.

6.2 Recommendations

This study found that LNG-ICE had high environmental, economic, and social sustainability among propulsion technologies with alternative fuels, which will help achieve UN SDGs 3, 7, 13, and 14. The conclusions of this environmental, economic, and social process evaluation can interest stakeholders related to research on LNG as a marine fuel for the ICE. However, because NG is a fossil fuel, the LNG supply-chain infrastructure may be affected due to the energy policies and laws of countries with high NG reserves.

Therefore, CH_4-ICE & SOFC, H_2-ICE & SOFC, and MeOH-SOFC were attributed approximately equal ranking scores. Moreover, if the value chain of production, supply, and utilization of green-hydrogen, ammonia, and methanol produced using RE is significantly improved, the ranking of this study may be reversed. In addition, hydrogen has validity and potential as a future marine fuel. However, many problems remain to be solved before it is commercialized through technological advances, and a more detailed further evaluation is required. Therefore, in summary, the following future research topics are proposed.

1) LNG importers must analyze their supply diversification policies to prepare for the risks of NG supply-chain disruptions arising from complex geopolitics.

2) Comparing hydrogen-, ammonia-, and methanol-SOFC systems with existing propulsion methods in terms of technical feasibility and rigorously evaluating the alternative fuel propulsion technology from a systems perspective considering safety.

3) Feasibility studies can evaluate the possibility of introducing green-hydrogen, ammonia, and methanol as marine fuels, including evaluations of fuel systems, bunkering, and safety routines.

4) Practical projects can test fuel-cell systems to demonstrate cost and durability considering business examples.

5) A further evaluation considering an energy system perspective with a more detailed description of shipping operations will enhance our understanding of the circumstances where alternative marine fuels are cost-effective.

Most importantly, the large-scale introduction of alternative marine fuels such as hydrogen, ammonia, and methanol must be supported by policy measures. The selection and design of these policies must be prepared ahead of technical feasibility, such as a reliable supply of fuel and available infrastructure, to prepare for a crisis in the rapidly changing energy market. In addition, energy policymaking will also affect the preconditions for various marine fuels. Uncertainty in policy and regulatory development will pose a major obstacle to the development of alternative fuels and RE applications.

For instance, developed, developing, and underdeveloped countries were all affected by the COVID-19 pandemic by 2022, causing the global economy to shrink. The crisis has significantly impacted the alternative fuels and RE industries due to border closures and reduced fuel and power demands. To overcome these policy and regulatory development uncertainties, complete information on policy planning, implementation, and modification should be shared with all participants to appeal to stakeholder participation. In addition, governments should provide buffers to investors in unexpected external crises. Accordingly, related stakeholders must take social responsibility and actively participate with government support. Therefore, policy analysis is also needed to clarify the impact of different policies and policy designs on marine fuel options.

References

Adachi, M., Kosaka, H., Fukuda, T., Ohashi, S., & Harumi, K. (2014). Economic analysis of trans-ocean LNG-fueled container ship. *Journal of Marine Science and Technology*, 19(4), 470–478. https://link.springer.com/article/10.1007/s00773-014-0262-5

Alaswad, A., Baroutaji, A., Achour, H., Carton, J., Al Makky, A., & Olabi, A. G. (2016). Developments in fuel cell technologies in the transport sector. International Journal of Hydrogen Energy, 41(37), 16499–16508. https://doi.org/10.1016/j.ijhydene.2016.03.164

Alkhaledi, A. N., Sampath, S., & Pilidis, P. (2022). Propulsion of a hydrogen-fuelled LH2 tanker ship. International Journal of Hydrogen Energy, 47(39), 17407–17422. https://doi.org/10.1016/j.ijhydene.2022.03.224

Amgad Elgowainy, Jeongwoo Han, and Hao Zhu. (2013). Updates to Parameters of Hydrogen Production Pathways in GREET.

Anand, S., & Sen, A. (2017). Human development and economic sustainability. Sustainability, 28(12), 421–441. https://doi.org/10.4324/9781315241951-37

Anil, M., Saygin, D., Miketa, A., Gielen, D., & Nicholas, W. (2016). The True Cost of Fossil Fuels: Saving on the Externalities of Air Pollution and Climate Change. Irena, 1–12. https://www.irena.org/-/media/files/irena/agency/publication/2016/irena_remap_externality_brief_2016.pdf

Ashrafi, M., Lister, J., & Gillen, D. (2022). Toward a harmonization of sustainability criteria for alternative marine fuels. Maritime Transport Research, 3(July 2021), 100052. https://doi.org/10.1016/j.martra.2022.100052

Balcombe, P., Staffell, I., Kerdan, I. G., Speirs, J. F., Brandon, N. P., & Hawkes, A. D. (2021). How can LNG-fuelled ships meet decarbonisation targets? An environmental and economic analysis. Energy, *227*, 120462. https://doi.org/10.1016/j.energy.2021.120462

Bicer, Y., & Khalid, F. (2020). Life cycle environmental impact comparison of solid oxide fuel cells fueled by natural gas, hydrogen, ammonia and methanol for combined heat and power generation. International Journal of Hydrogen Energy, 45(5), 3670–3685. https://doi.org/10.1016/j.ijhydene.2018.11.122

Burel, F., Taccani, R., & Zuliani, N. (2013). Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion. Energy, 57, 412–420. https://doi.org/10.1016/j.energy.2013.05.002

Čampara, L., Hasanspahić, N., & Vujičić, S. (2018). Overview of MARPOL ANNEX VI regulations for prevention of air pollution from marine diesel engines. SHS Web of Conferences, 58, 1–10. https://doi.org/10.1051/shsconf/20185801004

Cellek, M. S., & Pınarbaşı, A. (2018). Investigations on performance and emission characteristics of an industrial low swirl burner while burning natural gas, methane, hydrogen-enriched natural gas and hydrogen as fuels. International Journal of Hydrogen Energy, 43(2), 1194–1207. https://doi.org/10.1016/j.ijhydene.2017.05.107

Çetin, O., & Sogut, M. Z. (2021). A new strategic approach of energy management onboard ships supported by exergy and economic criteria: A case study of a cargo ship. Ocean Engineering, 219, 1–10. https://doi.org/10.1016/j.oceaneng.2020.108137

CHEK. (n.d.). About CHEK. https://www.projectchek.eu/

Cherp, A., & Jewell, J. (2011). The three perspectives on energy security: intellectual history, disciplinary roots and the potential for integration. Current Opinion in Environmental Sustainability, 3(4), 202–212. https://doi.org/10.1016/j.cosust.2011.07.001

Clarkson's Shipping Intelligence Network. (n.d.). Fleet > San Clemente 9,000. (2022). 2014, 40709. https://www.clarksons.net/n/#/SIN/register#/Fleet/Fleet/Individual-Vessels/documentId/40709

Clean Shipping Coalition, (n.d.). Air pollution from ships. https://www.cleanshipping.org/download/111128_Air%20pollution%20from%20ships_New_Nov-11(3).pdf

Clean Shipping Coalition, (n.d.). Air pollution from ships. https://www.cleanshipping.org/download/111128_Air%20pollution%20from%20ships_New_Nov-11(3).pdf

Clear Seas. (n.d.). Air pollution & marine shipping. https://clearseas.org/en/air-pollution/#:~:text=Commercial%20ships%20burn%20fuel%20for,SOx)%20and%20particulate%20matter.

Clift, R., & Druckman, A. (2015). Taking stock of industrial ecology. Taking Stock of Industrial Ecology, Cml, 1–362. https://doi.org/10.1007/978-3-319-20571-7

Comer, B., & Osipova, L. (2021). Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies. *International Council on Clean Transportation. Available online:* https://theicct.org/wp-content/uploads/2021/06/Well-to-wake-co2-mar2021-2. pdf (accessed on 4 March 2022).

Council of the European Union. (n.d.). Climate change: what the EU is doing. https://www.consilium.europa.eu/en/policies/climate-change/

Dalby, P. A., Gillerhaugen, G. R., Hagspiel, V., Leth-Olsen, T., & Thijssen, J. J. (2018). Green investment under policy uncertainty and Bayesian learning. Energy, 161, 1262-1281. https://doi.org/10.1016/j.energy.2018.07.137

David, L., Hao, C., Zhichao, W., Jennifer, K., May, W., Jeongwoo, H., Jennifer, D., Edward, F., John, S., Amgad, E., & Michael, W. (2014). Development of a Life Cycle Inventory of Water Consumption Associated with the Production of Transportation Fuels. https://greet.es.anl.gov/publication-water-lca

Diaz, M., Ortiz, A., & Ortiz, I. (2014). Progress in the use of ionic liquids as electrolyte membranes in fuel cells. Journal of Membrane Science, 469, 379–396. https://doi.org/10.1016/j.memsci.2014.06.033

DNV. (n.d.). Alternative fuel insight: Map. https://afi.dnv.com/Map

DNV. (n.d.). Alternative fuel insight: Statistics. https://afi.dnv.com/Statistics?repId=1

Dr Zabi, B. (2020). MARPOL Annex VI Chapter 4-Energy Efficiency Regulations National Workshop (virtual) on Ratification and Effective Implementation of MARPOL Annex VI for Egypt. November.

Ekener, E., Hansson, J., & Gustavsson, M. (2018). Addressing positive impacts in social LCA—discussing current and new approaches exemplified by the case of vehicle fuels. International Journal of Life Cycle Assessment, 23(3), 556–568. https://doi.org/10.1007/s11367-016-1058-0

EPA (Environmental Protection Agency). (2000). Using life cycle assessment to evaluate preferability of product. Framework for responsible environmental decision making. https://www.epa.gov/nrmrl/std/sab/lca/lca_fred.htm.

Fernández-Ríos, A., Santos, G., Pinedo, J., Santos, E., Ruiz-Salmón, I., Laso, J., Lyne, A., Ortiz, A., Ortiz, I., Irabien, Á., Aldaco, R., & Margallo, M. (2022). Environmental sustainability of alternative marine propulsion technologies powered by hydrogen - a life cycle assessment approach. Science of the Total Environment, 820, 153189 https://doi.org/10.1016/j.scitotenv.2022.153189

Fernando. (2022). Net Present Value (NPV). Investopedia. https://www.investopedia.com/terms/n/npv.asp

For methane, GWP 100 not measuring up. (2020). Clarity and Leadership for Environmental Awareness and Research at UC Davis. https://clear.ucdavis.edu/blog/methane-gwp100-not-measuring#:~:text=In%201990%2C%20scientists%20established%20GWP100,carbon%20dioxide%20over%20100%20years.

Gluch, P., & Baumann, H. (2004). The life cycle costing (LCC) approach: A conceptual discussion of its usefulness for environmental decision-making. Building and Environment, 39(5), 571–580. https://doi.org/10.1016/j.buildenv.2003.10.008

Grahn, M., Brynolf, S., & Taljegård, M. (2017). Electrofuels or Hydrogen as Marine Fuel: A Cost Comparison. Shipping in Changing Climates (SCC) Proceedings, 1–8. http://publications.lib.chalmers.se/records/fulltext/254511/local_254511.pdf

Haines, A., McMichael, A. J., Smith, K. R., Roberts, I., Woodcock, J., Markandya, A., Armstrong, B. G., Campbell-Lendrum, D., Dangour, A. D., Davies, M., Bruce, N., Tonne, C., Barrett, M., & Wilkinson, P. (2009). Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers. The Lancet, 374(9707), 2104–2114. https://doi.org/10.1016/S0140-6736(09)61759-1

Hertwich, E. G., Mateles, S. F., Pease, W. S., & McKone, T. E. (2001). Human toxicity potentials for life-cycle assessment and toxics release inventory risk screening. Environmental Toxicology and Chemistry: An International Journal, 20(4), 928–939. https://doi.org/10.1002/etc.5620200431

Hansson, J. (2020). Navigating towards low and potential zero carbon marine fuels. The Journal of Ocean Technology, 15(4). https://www.thejot.net/article-preview/?show_article_preview=1214

Hansson, J., Brynolf, S., Fridell, E., & Lehtveer, M. (2020). The potential role of ammonia as marine fuel-based on energy systems modeling and multi-criteria decision analysis. Sustainability, 12(8), 10–14. https://doi.org/10.3390/SU12083265

Howe, K. M. (1978). Capital Budgeting and Search: An Overview. Journal of Financial Research, 1(1), 23–33. https://doi.org/10.1111/j.1475-6803.1978.tb00003.x

Hwang CL & Yoon KP. (1981). Multiple Attribute Decision Making: methods and applications. Springer, New York.

IEA (2021), Hydrogen, IEA, Paris https://www.iea.org/reports/hydrogen

IEA. (n.d.). Methanol. https://www.iea-amf.org/content/fuel_information/methanol

International Energy Agency. (2022). Geopolitics of the energy transformation: the hydrogen factor. In IEA Publications. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf

IMO. (2022). Development of draft lifecycle GHG and carbon intensity guidelines for maritime fuels (draft LCA guidelines): ISWG-GHG 11/2/3, 28 January 2022.

IMO. (n.d.). Initial IMO GHG Strategy. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx

IMO. (n.d.). Nitrogen Oxides (NOx) – Regulation 13. https://www.imo.org/en/OurWork/Environment/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx

IMO. (n.d.). Prevention of Air Pollution from Ships. https://www.imo.org/en/OurWork/Environment/Pages/Air-Pollution.aspx

IMO. (n.d.). Sulphur oxides (SOx) and Particulate Matter (PM) – Regulation 14. https://www.imo.org/en/OurWork/Environment/Pages/Sulphur-oxides-(SOx)-%E2%80%93-Regulation-14.aspx

IPCC. (2021). Climate Change 2022:Impact, Adaptation and Vulnerability. https://www.ipcc.ch/report/ar6/wg2/

International Council on Clean Transportation. (2021). Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies. Journal of Geophysical Research Atmospheres, 118(11), 5380–5552.

Keeble, B. R. (1988). The Brundtland report: Our common future. *Medicine and War*, *4*(1), 17–25. https://doi.org/10.1080/07488008808408783

Khan, K., & Su, C. W. (2022). Does policy uncertainty threaten renewable energy? Evidence from G7 countries. Environmental Science and Pollution Research, 29(23), 34813–34829. https://doi.org/10.1007/s11356-021-16713-1

Lee, U., Han, J., Wang, M., Ward, J., Elliot, H., Dan, G., Rebecca, B., Per, H., Henrik, S., Parthav, D., Emmanuel, V., Patrik, K., Werner, W., Sandra, L.W., Heiko, M., Robert De, K., John, H., Tine, S., & Erik, F. (2016). Well-to-wheels emissions of greenhouse gases and air pollutants of dimethyl ether from natural gas and renewable feedstocks in comparison with petroleum gasoline and diesel in the United States and Europe. SAE International Journal of Fuels and Lubricants, *9*(3), 546–557. https://doi.org/10.4271/2016-01-2209

Li, H., Yang, S., & Qian, Y. (2012). Life cycle assessment of coal-based methanol. Computer Aided Chemical Engineering, 31, 530–534. https://doi.org/10.1016/B978-0-444-59507-2.50098-6

Lotfi, F. H., & Fallahnejad, R. (2010). Imprecise shannon's entropy and multi attribute decision making. Entropy, 12(1), 53–62. https://doi.org/10.3390/e12010053

M. Mintz, J. Han, M. Wang, C. Saricks. (2010). Well-to-Wheels Analysis of Landfill Gas-Based Pathways and Their Addition to the GREET Model http://greet.es.anl.gov/publication-xkdaqgyk0

Ma, S. (2020). Economics of Maritime Business. In Economics of Maritime Business. https://doi.org/10.4324/9781315658124

Maersk. (2021). A.P. Moller - Maersk accelerates fleet decarbonisation with 8 large ocean-going vessels to operate on carbon neutral methanol. https://www.maersk.com/news/articles/2021/08/24/maersk-accelerates-fleet-decarbonisation

MAN Energy Solutions. (n.d.). Methanol in shipping Marine Four-Stroke.

Mannucci, P. M., & Franchini, M. (2017). Health effects of ambient air pollution in developing countries. International journal of environmental research and public health, 14(9), 1–8. https://doi.org/10.3390/ijerph14091048

Manisalidis, I., Stavropoulou, E., Stavropoulos, A., & Bezirtzoglou, E. (2020). Environmental and health impacts of air pollution: a review. *Frontiers in public health*, *8*, 1–13. https://doi.org/10.3389/fpubh.2020.00014

Mao, X., Rutherford, D., Osipova, L., & Comer, B. (2020). Refueling assessment of a zero-emission container corridor between China and the United States: Could hydrogen replace fossil fuels? www.theicct.org.

Martin, A. (2021). A step forward for "green" methanol and its potential to deliver deep GHG reductions in maritime shipping. *ICCT*. https://theicct.org/a-step-forward-for-green-methanol-and-its-potential-to-deliver-deep-ghg-reductions-in-maritime-shipping%E2%80%AF/

Mekhilef, S., Saidur, R., & Safari, A. (2012). Comparative study of different fuel cell technologies. Renewable and Sustainable Energy Reviews, 16(1), 981–989. https://doi.org/10.1016/j.rser.2011.09.020

Michaels, E. (1989). Let patients see their medical records, Ontario college says. In Cmaj (Vol. 141, Issue 10). https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1451474/

Michael, C.J., Ignasi, P.-R., Edward, D.F. (2013). Energy consumption during the manufacture of nutrients for algae cultivation. http://greet.es.anl.gov/publication-johnson-nutrients

Ming, L., & Li, C. (2021). Methanol as a marine fuel. Nanyang Technological University, 36.

Ministry of the Environment, Government Offices of Sweden. (2020). Sweden's long-term strategy for reducing greenhouse gas emissions. Unfccc, December. https://unfccc.int/sites/default/files/resource/LTS1_Sweden.pdf

Montiel, I., Cuervo-Cazurra, A., Park, J., Antolín-López, R., & Husted, B. W. (2021). Implementing the United Nations' sustainable development goals in international business. Journal of International Business Studies, 52(5), 999–1030. https://doi.org/10.1057/s41267-021-00445-y

Nižić, F., Frančić, V., & Orović, J. (2017). Ships' solutions for meeting the International requirements regarding the reduction of Air Pollution. *Pomorski zbornik*, *53*(1), 53–65. https://hrcak.srce.hr/185472

Nordic Energy Research. (2021). The Nordic Maritime Transport and Energy Research Programme. https://www.nordicenergy.org/project/nordic-maritime-transport-and-energy-research-programme/

Nunes, R. A., Alvim-Ferraz, M. C., Martins, F. G., Peñuelas, A. L., Durán-Grados, V., Moreno-Gutiérrez, J., Jukka-Pekka, J., Hanna, H., & Sousa, S. I. (2021). Estimating the health and economic burden of shipping related air pollution in the Iberian Peninsula. Environment International, *156*, 1–11. https://doi.org/10.1016/j.envint.2021.106763

Pathways, N. Z. (2021). Facing the Future of Hydrogen: An International Guide. November. https://cms.law/en/media/expert-guides/files-for-expert-guides/the-promise-of-hydrogen-an-international-guide-nov-2021

Perčić, M., Vladimir, N., Jovanović, I., & Koričan, M. (2022). Application of fuel cells with zero-carbon fuels in short-sea shipping. Applied Energy, 309, 118463. https://doi.org/10.1016/j.apenergy.2021.118463

Peters, R. L. (1990). Effects of global warming on forests. Forest Ecology and Management, 35(1-2), 13–33. https://doi.org/10.1016/0378-1127(90)90229-5

Program, D. H. (2006). Hydrogen Fuel Cells Fact Sheet. U.S. Department of Energy, 2. https://www.californiahydrogen.org/wp-content/uploads/files/doe_fuelcell_factsheet.pdf

Projektgruppe ökologische Wirtschaft (Ed.). (1987). Produktlinienanalyse: Bedürfnisse, Produkte und ihre Folgen. Köln: Kölner Volksblattverlag.

Port of Rotterdam. (2018). Waste Disposal in the Ports of Rotterdam-Rijnmond. 31(January), 6622.

Putra, M. S. D., Andryana, S., Fauziah, & Gunaryati, A. (2018). Fuzzy analytical hierarchy process method to determine the quality of gemstones. Advances in Fuzzy Systems, 2018, 9094380. https://doi.org/10.1155/2018/9094380

Rao, R. V. (2007). Introduction to multiple attribute decision-making (MADM) methods. *Decision Making in the Manufacturing Environment: Using Graph Theory and Fuzzy Multiple Attribute Decision Making Methods*, 27–41. https://doi.org/10.1007/978-1-84628-819-7_3

Rashad, M., (2022). Analysis: Asian demand, rising costs squeeze Europe's LNG import plan. *Reuters.* https://www.reuters.com/business/energy/asian-demand-rising-costs-squeeze-europes-lng-import-plan-2022-06-23/

Rivera, A., Bravo, C., & Buob, G. (2017). Climate Change and Land Ice. In International Encyclopedia of Geography: People, the Earth, Environment and Technology. https://doi.org/10.1002/9781118786352.wbieg0538

Saxena, M. R., Maurya, R. K., & Mishra, P. (2021). Assessment of performance, combustion and emissions characteristics of methanol-diesel dual-fuel compression ignition engine: A review. Journal of Traffic and Transportation Engineering (English Edition), 8(5), 638–680. https://doi.org/10.1016/j.jtte.2021.02.003

SEA-LNG. (n.d.). The number of vessels using LNG as a marine fuel is growing rapidly. *Global fleet*. https://sea-lng.org/why-lng/global-fleet/

Schuller, O., Kupferschmid, S., Whitehouse, S., & Hengstler, J. (2019). Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel. Report, 158.

Smith, T. W., Jalkanen, J. P., Anderson, B. A., Corbett, J. J., Faber, J., Hanayama, S., ... & Pandey, A. (2015). Third IMO GHG study 2014, international maritime organization (IMO), London, UK.

Some climate change impacts irreversible for thousands of years, says IPCC report. (August 16, 2021). Safety4sea. https://safety4sea.com/some-climate-change-impacts-irreversible-for-thousands-of-years-says-ipcc-report/

Staffell, I., Scamman, D., Abad, A. V., Balcombe, P., Dodds, P. E., Ekins, P., ... & Ward, K. R. (2019). The role of hydrogen and fuel cells in the global energy system. Energy & Environmental Science, 12(2), 463–491. https://pubs.rsc.org/en/content/articlehtml/2019/ee/c8ee01157e

Stark, C., Xu, Y., Zhang, M., Yuan, Z., Tao, L., & Shi, W. (2022). Study on applicability of energy-saving devices to hydrogen fuel cell-powered ships. Journal of Marine Science and Engineering, 10(3), 388. https://doi.org/10.3390/jmse10030388

Stannard, S. (2020). COVID-19 in the maritime setting: the challenges, regulations, and the international response. Via Medica, 71(2), 85–90. https://journals.viamedica.pl/international_maritime_health/article/viewFile/69660/51219

Stančin, H., Mikulčić, H., Wang, X., & Duić, N. (2020). A review on alternative fuels in future energy system. Renewable and Sustainable Energy Reviews, 128, 109927. https://doi.org/10.1016/j.rser.2020.109927

Stamford, L. (2019). Life cycle sustainability assessment in the energy sector. Biofuels for a More Sustainable Future, *2020*, 115–163. https://doi.org/10.1016/B978-0-12-815581-3.00005-1

Strazza, C., Del Borghi, A., Costamagna, P., Traverso, A., & Santin, M. (2010). Comparative LCA of methanol-fuelled SOFCs as auxiliary power systems on-board ships. Applied Energy, 87(5), 1670–1678. https://doi.org/10.1016/j.apenergy.2009.10.012

Taljegard, M., Brynolf, S., Grahn, M., Andersson, K., & Johnson, H. (2014). Cost-effective choices of marine fuels in a carbon-constrained world: Results from a global energy model. Environmental Science and Technology, 48(21), 12986–12993. https://doi.org/10.1021/es5018575

Tam, I. C., Dev, A. K., Ng, C. W., Stoytchev, I., & Deltin, L. (2019). Engineering Design in Retrofitting LNG Fuel Tanks for Shipping in Combating Exhaust Emissions. Available at SSRN 3486748. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3486748

Tuné, M., Aakko-Sakasa, P., & Molander, P. (2018). SUMMETH-Sustainable Marine Methanol Deliverable D3. 1 Engine Technology, Research, and Development for Methanol in Internal Combustion Engines. Final Report. http://summeth.marinemethnol.com/reports/SUMMETH-WP3_fnl.pdf

United Nations. (2019). Climate change and poverty.

United Nations. (n.d.). Sustainability. https://www.un.org/en/academic-impact/sustainability

United Nations. (2020). The Sustainable Development Goals Report 2020. https://unstats.un.org/sdgs/report/2020/The-Sustainable-Development-Goals-Report-2020.pdf

United States Environmental Protection Agency (EPA), (n.d.). Nitrogen Oxides (NOx) Control Regulations. https://www3.epa.gov/region1/airquality/nox.html

U.S Department of Energy. (2015). Fuel Cells. *Energy Efficiency & Renewable Energy*. https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf

Valera-Medina, A., Xiao, H., Owen-Jones, M., David, W. I. F., & Bowen, P. J. (2018). Ammonia for power. Progress in Energy and Combustion Science, 69, 63–102. https://doi.org/10.1016/j.pecs.2018.07.001

Wang, Y., Wright, L., & Zhang, P. (2021). Economic feasibility of LNG fuel for trans ocean-going ships: A case study of container ships. Maritime Technology and Research, 3(2), 202–222. https://doi.org/10.33175/mtr.2021.248055

WMU. (2022). WMU hosts workshop on Ammonia and Hydrogen as maritime fuels. https://www.wmu.se/news/wmu-hosts-workshop-on-ammonia-and-hydrogen-as-maritime-fuels

World Health Organization. (2021). Urban Health Initiative a model process for catalysing change. https://www.who.int/publications/i/item/WHO-HEP-ECH-AQH-2021-2

Winnes, H., Styhre, L., & Fridell, E. (2015). Reducing GHG emissions from ships in port areas. Research in Transportation Business & Management, 17, 73–82. https://doi.org/10.1016/j.rtbm.2015.10.008

Zavadskas, E. K., Turskis, Z., & Kildiene, S. (2014). State of art surveys of overviews on MCDM/MADM methods. Technological and Economic Development of Economy, 20(1), 165–179. https://doi.org/10.3846/20294913.2014.892037

Ye, M., Sharp, P., Brandon, N., & Kucernak, A. (2022). System-level comparison of ammonia, compressed and liquid hydrogen as fuels for polymer electrolyte fuel cell powered shipping. International Journal of Hydrogen Energy, 47(13), 8565–8584. https://doi.org/10.1016/j.ijhydene.2021.12.164

Z. Yan. (2005). Chemical product life cycle evaluation of integrated environmental and economic performance, Guangzhou: South China University of Technology.

Appendices

Appendix 1

Research projects for alternative maritime fuels

Nordic Maritime Transport and Energy Research Program (NER)	
Research Projects	Research Contents
AEGIR [a]	AEGIR suggests a unique fuel-cell- and membrane-based system that efficiently converts green-ammonia into electrical energy. In the present concept, ammonia is: 1. cracked with hydrogen and nitrogen using a solid-oxide fuel cell, 2. hydrogen is produced and purified using a proton conductive electrochemical membrane (PEMFC), and 3. chemical energy is converted into electricity using PEMFC. Combining these three technologies, AEGIR aims to develop ammonia-fueled ship propulsion systems that provide high efficiency with low total system volume and weight, which are critical innovations in the project. In addition, this concept can prevent NOx emissions and significantly reduce CO_2 emissions. The byproduct of the fuel-cell electrical process is water.
CAHEMA [b]	CAHEMA studies a combination of ammonia and hydrogen to explore innovative injection and combustion strategies to reach reactivity-controlled compression ignition (RCCI) and direct-injection dual fuel stratification (DDFS) with these fuels. The project integrates advanced computational models with experimental techniques to design these engine concepts and evaluate their potential environmental, economic, and regulatory impacts.

HOPE [c]	HOPE involves developing and evaluating the conceptual design of ships for short-range transport using hydrogen as a fuel and fuel cells as a propulsive device. These include technical aspects as well as barriers and driving factors for the realization of ships and their impact on GHG emissions and air pollution in northern Europe.

[a] Ammonia electric marine power for GHG emission reduction

[b] Concepts of ammonia/hydrogen engines for marine application

[c] Hydrogen fuel cells solutions in shipping in relation to other low carbon options—a Nordic perspective

Note. Developed by Author (2022) based on NER (2021) and WMU (2022).

Appendix 2

Entropy method for objective weights for each attribute

R_{ij}	Attribute	GHG	AP	LCC	NPV	POCP	HTP
SOFC	CH_4	0.1228	0.0158	0.1003	0.1682	0.0102	0.0911
	H_2	0.1917	0.0658	0.1156	0.1371	0.1400	0.1001
	NH_3	0.0479	0.0188	0.1025	0.1642	0.2932	0.1120
	MeOH	0.2127	0.0413	0.1172	0.1359	0.0747	0.1541
ICE	CH_4	0.0863	0.0455	0.1207	0.1355	0.0337	0.0264
	H_2	0.0047	0.0817	0.1511	0.0798	0.0116	0.0522
	NH_3	0.1513	0.4981	0.1394	0.1010	0.3221	0.3158
	MeOH	0.1826	0.2329	0.1532	0.0780	0.1141	0.1478
$R_{ij} ln R_{ij}$	Attribute	GHG	AP	LCC	NPV	POCP	HTP
SOFC	CH_4	−0.257	−0.065	−0.231	−0.299	−0.046	−0.218
	H_2	−0.316	−0.179	−0.249	−0.272	−0.275	−0.230
	NH_3	−0.145	−0.074	−0.233	−0.296	−0.359	−0.245
	MeOH	−0.329	−0.131	−0.251	−0.271	−0.193	−0.288
ICE	CH_4	−0.211	−0.141	−0.255	−0.270	−0.114	−0.096
	H_2	−0.025	−0.204	−0.285	−0.202	−0.052	−0.154
	NH_3	−0.285	−0.347	−0.274	−0.232	−0.365	−0.364
	MeOH	−0.310	−0.339	−0.287	−0.199	−0.247	−0.282
$\sum_{i=1}^{N} R_{ij} ln R_{ij}$	Attribute	GHG	AP	LCC	NPV	POCP	HTP
		−1.881	−1.483	−2.067	−2.043	−1.654	−1.879
k = 0.7213		GHG	AP	LCC	NPV	POCP	HTP
e_j		0.905	0.713	0.994	0.982	0.795	0.903
d_j		0.095	0.286	0.005	0.017	0.204	0.096
w_j (%)		13.47	40.67	0.80	2.44	28.96	13.65
Attribute		Environment		Economic		Social	
Total (%)		54.15		3.25		42.61	

Note. Developed by Author (2022).

Appendix 3

TOPSIS analysis for ranking alternatives in terms of sustainability

SOFC	LNG	Hydrogen	Ammonia	Methanol
GHG	0.41	0.64	0.16	0.71
AP	0.00036	0.00151	0.00043	0.00095
LCC	877,148,674$	1,010,366,609$	896,129,000$	1,024,431,791$
NPV	463,899,002$	378,160,162$	452,875,106$	375,006,976$
POCP	0.0000279	0.000382	0.0008	0.000204
HTP	0.00559	0.00614	0.00687	0.00945
ICE	LNG	Hydrogen	Ammonia	Methanol
GHG	0.28804	0.01570	0.50518	0.60969
AP	0.00104	0.00187	0.01141	0.00533
LCC	1,055,463,207$	1,320,739,919$	1,218,998,097$	1,339,619,327$
NPV	373,531,927$	220,270,073$	278,588,969$	215,221,990$
POCP	0.000092	0.000032	0.000878	0.000311
HTP	0.00162	0.00320	0.01936	0.00906
Attribute Weights	Environment: 54.15 %, Economic: 3.25 %, and Social: 42.61 %			
Cost (1)	GHG, LCC, AP, POCP, and HTP			
Benefit (0)	NPV			

	LNG	
LCSA	Normalized decision	Weighted normalized matrix
GHG	0.3041 (SOFC) 0.2136 (ICE)	0.0409 (SOFC) 0.0287 (ICE)
AP	0.0281 (SOFC) 0.0807 (ICE)	0.0114 (SOFC) 0.0328 (ICE)
LCC	0.2804 (SOFC) 0.3374 (ICE)	0.0022 (SOFC) 0.0027 (ICE)
NPV	0.4602 (SOFC) 0.3705 (ICE)	0.0112 (SOFC) 0.0090 (ICE)
POCP	0.0213 (SOFC) 0.0704 (ICE)	0.0061 (SOFC) 0.0204 (ICE)
HTP	0.2151 (SOFC) 0.0623 (ICE)	0.0293 (SOFC) 0.0085 (ICE)

	Hydrogen	
LCSA	Normalized decision	Weighted normalized matrix
GHG	0.4747 (SOFC) 0.0116 (ICE)	0.0639 (SOFC) 0.0015 (ICE)

AP	0.1169 (SOFC) 0.1448 (ICE)	0.0475 (SOFC) 0.0589 (ICE)
LCC	0.3230 (SOFC) 0.4222 (ICE)	0.0025 (SOFC) 0.0033 (ICE)
NPV	0.3751 (SOFC) 0.2185 (ICE)	0.0091 (SOFC) 0.0053 (ICE)
POCP	0.2923 (SOFC) 0.0243 (ICE)	0.0846 (SOFC) 0.0070 (ICE)
HTP	0.2362 (SOFC) 0.1232 (ICE)	0.0322 (SOFC) 0.0168 (ICE)

	Ammonia	
LCSA	Normalized decision	Weighted normalized matrix
GHG	0.1186 (SOFC) 0.3747 (ICE)	0.0159 (SOFC) 0.0504 (ICE)
AP	0.0333 (SOFC) 0.8836 (ICE)	0.0135 (SOFC) 0.3594 (ICE)
LCC	0.2865 (SOFC) 0.3897 (ICE)	0.0023 (SOFC) 0.0031 (ICE)
NPV	0.4493 (SOFC) 0.2763 (ICE)	0.0109 (SOFC) 0.0067 (ICE)
POCP	0.6123 (SOFC) 0.6726 (ICE)	0.1773 (SOFC) 0.1948 (ICE)
HTP	0.2643 (SOFC) 0.7450 (ICE)	0.0360 (SOFC) 0.1016 (ICE)

	Methanol	
LCSA	Normalized decision	Weighted normalized matrix
GHG	0.5266 (SOFC) 0.4522 (ICE)	0.0709 (SOFC) 0.0609 (ICE)
AP	0.0732 (SOFC) 0.4132 (ICE)	0.0297 (SOFC) 0.1680 (ICE)
LCC	0.3275 (SOFC) 0.4283 (ICE)	0.0026 (SOFC) 0.0034 (ICE)
NPV	0.3720 (SOFC) 0.2135 (ICE)	0.0090 (SOFC) 0.0052 (ICE)
POCP	0.1561 (SOFC) 0.2381 (ICE)	0.0452 (SOFC) 0.0689 (ICE)
HTP	0.3636 (SOFC) 0.3487 (ICE)	0.0496 (SOFC) 0.0475 (ICE)

Option	GHG	AP	LCC	NPV	POCP	HTP
Positive ideas	0.00156	0.01143	0.00225	0.01123	0.00618	0.00851
Negative ideas	0.07095	0.35940	0.00344	0.00521	0.19480	0.10167

Option	LNG	Hydrogen	Ammonia	Methanol
Separation from Positive ideas	0.0445 (SOFC) 0.0375 (ICE)	0.1092 (SOFC) 0.0486 (ICE)	0.1739 (SOFC) 0.4095 (ICE)	0.0914 (SOFC) 0.1832 (ICE)
Separation from Negative ideas	0.4035 (SOFC) 0.3840 (ICE)	0.3380 (SOFC) 0.3708 (ICE)	0.3567 (SOFC) 0.0205 (ICE)	0.3657 (SOFC) 0.2354 (ICE)
P_i	0.90051 (SOFC) 0.91103 (ICE)	0.75581 (SOFC) 0.88412 (ICE)	0.67218 (SOFC) 0.04772 (ICE)	0.79988 (SOFC) 0.56242 (ICE)
Rank	2 (SOFC) 1 (ICE)	5 (SOFC) 3 (ICE)	6 (SOFC) 8 (ICE)	4 (SOFC) 7 (ICE)

Note. Developed by Author (2022).