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Master Thesis

Life Cycle Assessment of ammonia vs liquefied natural gas in a sea going shipping vessel.

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ABSTRACT:
The shipping industry across the globe is being put under severe pressure to reduce greenhouse gas (GHG) emissions to ensure that it meets international climate targets. This has led to an increased interest and necessity of alternative marine fuels that can contribute towards decarbonization of the shipping industry. In this context, liquefied natural gas (LNG) and green ammonia are often reported among other alternative marine fuels currently under consideration as a way of decarbonizing the maritime industry. LNG is considered as the transitional fuel whereas ammonia being carbon free is a promising net zero carbon option. The environmental performance of these alternative marine fuels remains uncertain due to the limited availability of life cycle assessment (LCA) studies on these emerging options. The existing LCA studies are limited by their inconsistency and transparency towards methodological choices and assumptions, raising concerns about the reliability of the results. This study aims to compare the environmental performance of LNG and green ammonia with respect to their applicability to the maritime industry in terms of their global warming potential (GWP). A tank to wake (TTW) LCA framework has been used to analyse the emissions related to fuel combustion. The study is conducted on a real offshore supply vessel operating on a selected route with a functional unit of one complete round trip. A transparent Excel based LCA model was developed to calculate the total energy demand, fuel consumption, emissions associated with both configurations and their respective GWP. The results suggest that the comparative climate performance of the two fuels is strongly dependent on pollutant specific emissions as well as emission control assumptions. Emissions from both ammonia and LNG fuel pathways are key drivers of GWP. In the case of ammonia, nitrogen oxides (NOx), nitrous oxide (N_2O), and unburned ammonia (ammonia slip) are particularly significant, while for LNG, carbon dioxide (CO_2) and methane (CH_4) emissions play a dominant role in shaping overall climate impact. Without any emission control measures, ammonia combustion has a higher GWP when compared to LNG, as it is dominated by N_2O with a very potent GWP potential. Scenario-based analysis is performed to study the effect of catalytic emission control systems on N_2O emissions related to ammonia-fuelled engine systems. The results show that the environmental performance of green ammonia strongly depends on the integration of emissions reduction technology. Even the conservative efficiency of the selective catalytic reduction (SCR) exhibits much lower overall GHG emissions as compared to LNG. Overall, the findings suggest that LNG can serve as a transitional fuel by offering lower emissions compared to conventional marine fuels, whereas green ammonia holds significant long-term potential for maritime decarbonization, provided that nitrogen-related emissions are effectively controlled.

KEYWORDS: Life Cycle Assessment, Alternative Marine Fuels, Maritime Decarbonization, Greenhouse Gas Emissions, Green Ammonia, Liquefied Natural Gas

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Abbreviations

AIS	Automatic Identification System
CCS	Carbon Capture and Storage
CH_4	Methane
CO_2	Carbon Dioxide
DP	Dynamic Positioning
GHG	Greenhouse Gas
GWP	Global Warming Potential
IMO	International Maritime Organization
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
MGO	Marine Gas Oil
N_2	Nitrogen
N_2O	Nitrous Oxide
NH_3	Ammonia
NO_x	Nitrogen Oxides
PSV	Platform Supply Vessel
SCR	Selective Catalytic Reduction
TTW	Tank-to-Wake
WTT	Well-to-Tank
WTW	Well-to-Wake

1 Introduction

Maritime shipping is essential to global trade, carrying about 80–90% of goods by volume across the world. This volume is even higher in developing economies where seaborne transport remains the primary conduit to participate in global supply chains and international markets. Without maritime shipping, international trade, everyday life, and global economies would be totally different than as they are currently. As the global population increases, the need for goods grows, and shipping plays a major role in delivering them efficiently (International Chamber of Shipping, n.d.; United Nations Conference on Trade and Development, 2025).

Within this global landscape, the European Union (EU) plays a major role in maritime transport. Shipping handles more than 75% of the EU's external trade and about 33% of trade within the EU. The European maritime sector accounts for more than 40% of the global merchant fleet. In addition, maritime transport and related activities generate roughly 40% of the total value added and 24% of employment in the EU blue economy, highlighting both the sector's economic importance to Europe and the region's strong influence on the future of global shipping (Fratila et al., 2021).

The vast scale of maritime transport and its associated activities result in substantial environmental impacts worldwide. According to the (IMO, 2020) global shipping accounted for 2.89% of global human-caused GHG emissions in 2018, corresponding to approximately 1076 million tonnes of CO_2 (European Commission, n.d.) Without further mitigation measures, emissions from shipping could rise to 90% and 130% of their 2008 levels by 2050 (IMO, 2020, 2023), which would threaten the achievement of the Paris Agreement climate targets.

At the European level, maritime transport is a non-negligible contributor to GHG emissions, representing 3 to 4% of total EU CO_2 emissions, or more than 124 million tonnes of CO_2 in 2021. This continued increment in shipping emissions, if left unchecked and unmitigated, would undermine the EU’s climate goals and its commitments to Paris Agreement (European Comission, 2023).

To curb this global shipping emissions trend, the International Maritime Organization (IMO) introduced an updated strategy (IMO, 2023) aimed at reducing GHG from global maritime transport, with the goal of reaching net-zero emissions by approximately 2050. The strategy also outlines interim targets, including a reduction in total annual emissions of at least 20%, with an ambition of 30%, by 2030, and at least 70%, with an ambition of 80%, by 2040, relative to 2008 levels. These milestones are intended to align maritime decarbonization efforts with the long-term global warming objectives under the Paris Agreement.

To support the role of maritime transport in achieving climate neutrality, the EU has introduced binding regulatory measures. This includes expanding the EU Emissions Trading System (EU ETS) to apply to CO_2 emissions since January 2024, with CH_4 and N_2O emissions set to be incorporated from 2026 for all large ships operating at EU ports. By introducing a carbon cost on shipping operations, the policy is designed to encourage and speed up the transition toward cleaner, low-emission fuel alternatives (European Comission, n.d.).

Rising emissions, combined with global targets under the IMO framework, and strict regional policies within the EU have significantly increased regulatory pressure on the shipping industry. As a result, industry actors must rapidly adopt cleaner technologies, transition to carbon free fuels, and adapt their operations under increasing time pressure. This situation underscores the need for immediate and collective efforts to advance maritime decarbonization worldwide (European Comission, n.d.; IMO, 2023; Q. Wang et al., 2023).

1.1 Problem formulation

Despite the increased need and interest for alternative marine fuels, there remains no clear agreement on how different options compare in terms of climate impact within the shipping sector (Roux et al., 2024). Among the leading candidates, liquified natural gas (LNG) and ammonia are often considered potentially promising options to reduce GHGs. LNG is considered as a transitional fuel because it is already supported by the existing established infrastructure and produces less carbon emissions as compared to conventional fuels. Whereas green ammonia is often positioned as a future fuel option capable of supporting the complete elimination of carbon emissions in maritime transport.

However, the environmental performance of these fuels remains uncertain because of lack of LCA studies focusing on these alternatives, inconsistent LCA methodologies, limited real vessel case studies, and varying treatment of emissions reduction technologies. Existing LCA research on alternative marine fuels remains sparse overall. While LNG has been examined a little more, ammonia is significantly underrepresented in the maritime LCA literature. In fact, majority of these studies focus on fossil-based ammonia, and studies on the LCA of green ammonia remain very limited (Roux et al., 2024). Thus, the environmental implications of these fuels remain under explored, reducing the reliability and comparability of the results, and limiting the ability of current literature to evaluate their role in maritime decarbonization.

Another challenge is that the existing literature indicates highly contrasting LCA results when comparing LNG and ammonia. These inconsistencies are largely driven by methodological choices, including selection of system boundaries, functional units, emission factors, and assumptions regarding engine operation and emission control technologies. Especially the handling of emissions treatment is a decisive factor due to the high GWP of the GHGs.

Furthermore, there is a lack of transparency in the existing studies as many of them rely on generic assumptions and aggregated modeling approaches limiting reproducibility, addressing sensitivity analysis and interpretation of results. The reviewed literature shows that the existing state of comparative LCA studies is limited by a lack of methodological consistency and transparency (Y. Wang et al., 2025a). To address these uncertainties and limitations, this study examines the comparative GHG performance of green ammonia and LNG as marine fuels under a transparent TTW phase applied to case vessel with clearly defined operating conditions. The key challenges identified in the literature are outlined in Table 1 and are explored further in chapter 2.

Table 1. Key challenges in the existing literature on the LCA of LNG and ammonia as marine fuel alternatives (Roux et al., 2024; Y. Wang et al., 2025a; B. A. Zincir & Arslanoglu, 2024; Zou & Yang, 2023).

Problem Category	Description of Issue	Implication for Research
Lack of Consensus	There is no clear agreement in the literature regarding the relative climate performance of alternative marine fuels, particularly LNG and ammonia.	Creates uncertainty for stakeholders and weakens the basis for decision-making in maritime decarbonization.
Limited LCA Studies	The number of LCA studies on alternative marine fuels are low. Ammonia, especially green ammonia, is significantly underrepresented.	Results in insufficient evidence to robustly evaluate and compare fuel options.
Methodological Inconsistency	Existing studies use varying system boundaries, functional units, emission factors, and assumptions on engine operation and emission control technologies.	Leads to poor comparability and conflicting results across studies.

Problem Category	Description of Issue	Implication for Research
Contradictory Results	Literature reports highly divergent LCA outcomes when comparing LNG and ammonia.	Reduces reliability and confidence in conclusions drawn from existing research.
Emission Treatment Uncertainty	Differences in how emissions and after-treatment systems are modelled significantly affect results, especially due to high GWP gases.	Introduces major variability and potential bias in climate impact assessments.
Lack of Real-World Case Studies	Limited application of LCA to real vessel operations with defined conditions.	Restricts practical relevance and applicability of findings.
Data Transparency Issues	Many studies rely on generic assumptions and aggregated models with limited transparency.	Limits reproducibility, sensitivity analysis, and critical evaluation of results.
Underexplored Environmental Impacts	Environmental implications of LNG and ammonia remain insufficiently studied.	Weakens the ability to assess their true potential for maritime decarbonization.
Comparability Limitations	Lack of standardized approaches across studies.	Prevents meaningful cross-study comparisons and synthesis of findings.

1.2 Research goal and objectives

This study aims to assess and compare the GHG emissions of green ammonia and LNG as marine fuel alternatives by analyzing their GWP within a TTW LCA framework, using a representative offshore supply vessel as the case study. In addition, the study aims to assess the suitability of Microsoft Excel for conducting TTW LCA in comparison to conventional LCA tools.

The study pursues the following objectives to achieve this aim.

i. To develop a transparent TTW LCA framework for evaluating operational emissions.
ii. To develop a voyage-based energy demand model for the case vessel under transparent operational assumptions.
iii. To estimate the fuel consumption per trip for both configurations:
    - Green ammonia with pilot marine gas oil (MGO)
    - LNG with pilot MGO
iv. To quantify the GHG emissions including CO_2, CH_4, N_2O, and ammonia slip depending on the fuel configuration.
v. To calculate the GWP of both fuel configuration in terms of CO_2 equivalent ($KgCO_2e$) using IPCC’s 100-year GWP factors.
vi. To analyze the effect of N_2O emissions and SCR after treatment scenarios on the climate performance of the green ammonia fuel.
vii. To compare the overall GHG performance of green ammonia and LNG under the defined operating conditions.
viii. To evaluate the applicability of a spreadsheet-based LCA approach (Microsoft Excel) and compare its effectiveness and transparency with conventional LCA software tools.

1.3 Study scope and limitations

In this study, the GHG performance of the two alternative fuels is evaluated solely within a TTW LCA boundary. The analysis is restricted to emissions generated during onboard fuel use and does not account for upstream stages such as production, storage, or distribution. As a result, well-to-tank (WTT) emissions are excluded from the system boundary.

This allows a focused comparison of operational emissions of both fuel configurations under the consistent operating conditions.

The study is carried out using a representative offshore supply vessel, named Viking Energy, on a selected route. The functional unit is one complete round trip between the onshore supply base at Mongstad and the offshore destination at Oseberg. Having the defined vessel and route, this study aims to provide a realistic scenario to compare the GHG emissions between both configurations.

This study has its own limitations which should be considered when interpreting the results. Firstly, this study is limited to a single vessel type and operational route which may not represent other vessel types, sizes or operational profiles. Secondly, the operational profile of the vessel such as speed, engine load, auxiliary power demand, maneuvering duration, and pilot fuel fraction is based on assumptions which may differ than the actual vessel operational profile.

Moreover, the emission factors are taken from peer-reviewed studies which may not reflect the real-world GHG emission performance of the vessel since factors such as engine type, operating conditions, and fuel composition can vary and significantly affect results. Lastly, there is inherent uncertainty in the aftertreatment of N_2O emissions and the efficiency of SCR strategies to reduce these emissions for the ammonia fueled engine. Experimental studies have shown that N_2O conversion efficiency in SCR systems depends on catalyst characteristics and exhaust conditions; hence, scenario-based assumptions are made in this study to represent possible conditions. These limitations define the scope of this study and should be considered when interpreting the results of this study.

1.4 Thesis structure

This thesis is organized into seven chapters. Chapter 1 provides an introduction to the research topic, background and context of maritime decarbonization, followed by the problem statement of the study, research aims and objectives, and then finally the scope and limitations of the study.

Chapter 2 presents the literature review on alternative marine fuels and their role for maritime decarbonization, and LCA in the maritime sector. It reviews and discusses the existing life cycle studies on the ammonia and LNG as alternative marine fuels. It also presents methodological variations, key challenges and research gaps in the existing LCA literature.

Chapter 3 describes the methodology of the study. It outlines the goal and scope of the study, data collection process, measurement units and conventions, operational assumptions, life cycle inventory (LCI), operational energy demand and fuel consumption calculations, and emissions and impact calculations.

Chapter 4 reports the study's findings, including fuel consumption and emissions as well as GWP for both configurations. It also includes break-even analysis and scenario-based SCR treatment results.

Chapter 5 interprets the results in relation to the research objectives and existing literature, highlighting key findings and their implications. It also discusses the limitations of the LCA methodology of the study.

Chapter 6 is dedicated to the presentation of the conclusions from the thesis, where the main contributions and findings from the research are presented, while also highlighting the potential for further research in the area.

Chapter 7 summarizes the thesis, outlining the research motivation, methodology, key findings, and its contribution to the existing literature.

2 Alternative marine fuels and their role for maritime decarbonization

This chapter critically examines prior research on alternative marine fuels and the use of LCA in the maritime sector. It focuses on how earlier studies have evaluated the environmental impacts of different fuel options and the methods they have applied. Particular attention is given to ammonia and LNG, as these fuels are central to this study and are frequently discussed in relation to maritime decarbonization. The chapter concludes on methodological variations, key challenges, and research gaps in the existing LCA studies on alternative marine fuels.

In the context of green shipping development, studies focused on the research and development of alternative marine fuels (Barone et al., 2026; Y. Wang et al., 2025a; Zhang et al., 2025) show that conventional fuels such as heavy fuel oil (HFO), MGO, and marine diesel oil (MDO) remain highly carbon intensive. Operational and technical measures such as voyage optimization, weather routing, slow steaming, lubricants, advanced propellers, and hull modifications may contribute to short term regulatory compliance, but they remain insufficient to achieve long term environmental sustainability.

As a result, continued reliance on conventional marine fuels, interim technical and operational measures is identified as incompatible with stricter global climate targets. Therefore, shifting away from conventional fossil fuels has become a critical step, with countries and organizations increasingly adopting low carbon and zero carbon fuels to solve the current environmental problems (Y. Wang et al., 2025a; Zhang et al., 2025).

In response to these limitations, literature (Barone et al., 2026; Li et al., 2025; Zhang et al., 2025) currently identifies a range of candidates mainly LNG, Methanol, Hydrogen, Ammonia, and biodiesel as potential alternative marine fuels to reduce life cycle GHG emissions from maritime transport.

Comparative decarbonization pathway studies (Barone et al., 2026) highlight that the effectiveness of these alternative fuels varies across ship classification and operational profiles, meaning that no single fuel pathway is universally applicable. Differences in technological maturity, infrastructure readiness, scalability, and life cycle GHG emissions further reinforce the need for context specific fuel evaluation (Barone et al., 2026; Zhang et al., 2025). In this setting, a conceptual distinction between transitional and long-term fuel strategies is commonly reported, with fuels such as LNG and methanol framed as transitional options due to their partial emission reduction potential, and long-term options, including ammonia and hydrogen, that have the potential to support deep decarbonization (Barone et al., 2026; Zhang et al., 2025).

Among long-term fuel options, ammonia is gaining increasing attention as a promising alternative because it contains no carbon (Cheng et al., 2025). Its compatibility with the internal combustion engine-based propulsion systems, motivating a more detailed examination of its opportunities and challenges in the following sections.

2.1.1 Conventional and transitional marine fuels

Traditional marine fuels such as HFO, MGO, and MDO have long been the dominant choice in global shipping due to their high energy density, well-established fuel supply chain infrastructure, and compatibility with marine propulsion systems. Nevertheless, the combustion of these fuels is known to emit substantial amounts of CO_2, NO_x, SO_x, and particulate matter (PM), which has been increasingly regulated. Consequently, LNG is often considered the most widely adopted transitional fuel in shipping because it significantly reduces SOx, NOx, and particulate emissions, while also offering lower CO_2 emissions compared to conventional fuels, making it suitable for long-distance operations (Y. Wang et al., 2025a).

LNG mainly comprises CH_4 in large quantities and smaller amounts of other light hydrocarbon gases like ethane and propane. Large-scale marine-based LNG is mostly produced from fossil-based natural gas. There is an increasing interest in bio-LNG and synthetic

LNG referred to as e-LNG for future decarbonization. The LNG supply chain involves natural gas extraction, followed by processing and liquefaction, then transportation, and finally storage in double-walled cryogenic tanks at very low temperatures. LNG is utilized in steam turbines, monofuel gas engines, and dual-fuel gas engines in which LNG is burned in combination with a pilot quantity of diesel fuel (Fun-sang Cepeda et al., 2019; Srinivasan et al., 2024).

The advantages of marine LNG include lower CO_2 emissions per unit of energy generated when compared with conventional marine fuels, near zero SO_x emissions, less formation of PM, and conformity with existing emission control area requirements (Schernikau & Smith, 2022). Furthermore, the technology is mature and highly compatible with existing ship designs, and the rapidly increasing infrastructure for bunkering the fuel has facilitated its widespread adoption. At the end of 2023, LNG had become the major fuel for alternative-fueled vessels in operation worldwide, further emphasizing the role of the fuel in the transition. A recent comparative review on the alternative fuels (Li et al., 2025) have concluded that LNG is a transitional fuel for the marine sector, given its capacity for the significant reduction of CO_2, SO_x, and PM emissions when compared with conventional fuels, although the fuel storage and safety issues must be considered.

Despite these benefits, however, LNG has significant drawbacks as a long-term decarbonization strategy. Methane slip, or the amount of CH_4 released during combustion and within the fuel chain, is a major concern as a GHG, given its 100-year GWP potential of 28 and 82 over a 20-year period compared to CO_2. Thus, while LNG may be seen as a short-term solution to some emissions, it is now considered an insufficient strategy for achieving a zero-emissions shipping industry without significant mitigation of methane slip or a transition to renewable LNG fuels (Y. Wang et al., 2025a).

2.1.2 Emerging low and carbon free marine fuels

As the maritime sector works toward decarbonization targets, a range of alternative fuels has gained attention, including hydrogen, methanol, and ammonia. These options differ widely in carbon content and storage requirements, leading to distinct environmental trade-offs for each option (Y. Wang et al., 2025a). LNG, methanol, hydrogen, and ammonia vary significantly in their effectiveness to reduce emissions and in their storage complexity. These differences highlight the need for fuel choice in line with specific environmental and operational requirements (Li et al., 2025).

Hydrogen can serve as a marine fuel in both compressed gas and liquefied forms, and it can be generated through a variety of routes, including electrolysis, steam methane reforming, and other biological or thermochemical processes. Despite the availability of these pathways, steam methane reforming remains the primary production method, but it is associated with substantial upstream CO_2 emissions unless integrated with carbon capture and storage (CCS), resulting in what is known as blue hydrogen (Carapellucci & Giordano, 2020; Yasemi et al., 2023). In contrast, hydrogen produced via water electrolysis using renewable energy has minimal upstream emissions but remains constrained by high costs, limited infrastructure, and challenges related to storage and handling. In maritime applications, hydrogen can be utilized either in fuel cells or internal combustion engines, with fuel cells more commonly adopted in pilot projects due to their higher efficiency and lower emissions. Nevertheless, its practical use is still restricted by low energy density, safety concerns, and difficulties in scaling power for larger vessels (Y. Wang et al., 2025b). Figure 1 shows the production sources, production methods and power applications of hydrogen.

Figure 1. Preparation sources, preparation methods, and power applications of hydrogen (Y. Wang et al., 2025a).

Methanol is considered a low-carbon marine fuel with practical advantages, as it remains liquid at ambient conditions and can be stored and transported using modified versions of existing fuel infrastructure. It can be produced through multiple pathways, including fossil sources such as natural gas and coal, as well as more sustainable routes like biomass conversion and e-methanol synthesis using captured CO_2 and renewable hydrogen. While fossil-derived methanol currently dominates, increasing attention is being given to green methanol in decarbonization strategies (Wu & Lin, 2025).

In terms of application, methanol can be used in both single- and dual-fuel engines and offers environmental benefits such as negligible SOx and particulate emissions, along with lower NOx compared to conventional marine fuels. It also has a relatively high technology readiness level and is easier to store than hydrogen, making it a strong candidate for near- to mid-term adoption, particularly if sustainable production pathways can be expanded (Y. Wang et al., 2025a). Figure 2 summarizes the preparation sources, preparation methods and power applications of methanol.

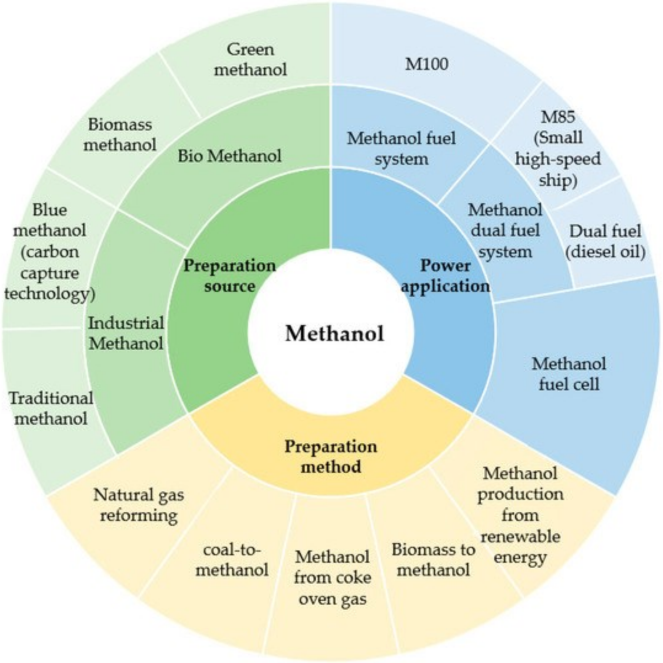


Figure 2. Sources, production pathways, and power applications of methanol (Y. Wang et al., 2025a).

Ammonia and hydrogen are different from methanol in that they do not have any carbon in their molecular composition, making them carbon-free at the time of combustion. Due to this fact, ammonia has started gaining more importance as a zero-carbon fuel for ships to attain decarbonization. Ammonia is more appealing than hydrogen because it is easier to store and handle. Nevertheless, the environmental implications of ammonia use are highly dependent on production routes, engine types, and emission mitigation measures, making ammonia different from other low-carbon marine fuels (Y. Wang et al., 2025a).

Moreover, ammonia is frequently cited as a hydrogen carrier rather than a standalone fuel due to its higher volumetric hydrogen content and lower storage requirements compared to hydrogen, making it more feasible to store onboard ships (Duong & Kang, 2025).

2.1.3 Ammonia as a marine fuel

With increasing pressure to decarbonize the maritime sector, ammonia has gained attention as a viable fuel option due to its carbon free nature (Pachiannan et al., 2025). It also benefits from the ability to be produced at industrial scale, supporting its potential for widespread adoption. Ammonia's preparation method, its types and power applications are highlighted in Figure 3. A recent review study (Jayabal, 2024) indicates that, in efforts to reduce GHG emissions, green ammonia has gained strong attention due to its carbon free nature, relatively high volumetric energy density, and ease of storage and transport. These characteristics strengthens its ability to serve as a long-term marine fuel choice capable of supporting ambitious GHG reduction targets. Though it is accompanied by technical and environmental challenges which need to be addressed.

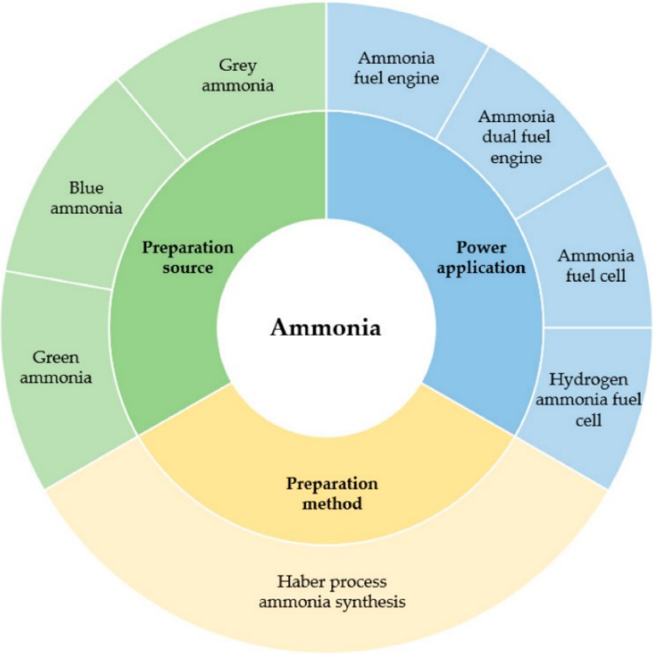


Figure 3. Production pathways, variants, and power applications of ammonia (Y. Wang et al., 2025a).

Ammonia production involves two main gases: nitrogen (N_2) and H_2. N_2 is obtained from the air, while H_2 is usually the main contributor to both the cost and environmental impact of the process. Equation (1) represents the exothermic reaction to produce ammonia which releases 92.4 kJ mol^{-1} of energy (Tornatore et al., 2022).

$$N_2 + 3H_2 \rightarrow 2NH_3 \quad (1)$$

Currently the main process used to achieve this reaction is Haber-Bosch (HB) process, where N_2 reacts with hydrogen under high pressure and temperature in the presence of a catalyst as shown in Figure 4. This is the oldest and most well-established process, but it is highly energy intensive, requiring roughly 26 GJ to produce one tonne of ammonia. The reaction takes place in the presence of a catalyst at pressures of 50 to 200 bar and temperatures between 650 and 750 K (Fúnez Guerra et al., 2020).

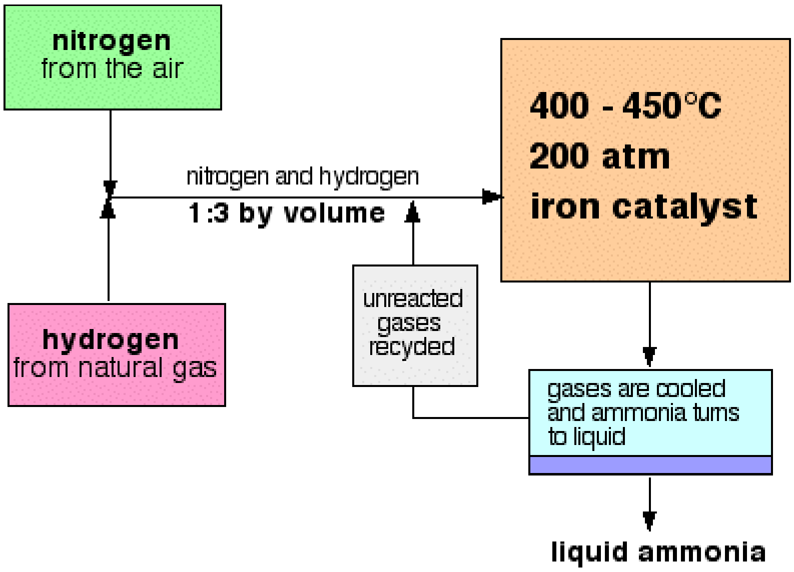


Figure 4. Scheme of Haber-Bosch Process (Jim Clark, n.d.).

Several catalysts can be used for this process, however iron-based catalysts promoted with potassium hydroxide are most commonly used. The ammonia produced exits the reactor as a hot, pressurized gas and must be cooled and condensed into liquid form for collection. Unreacted nitrogen and hydrogen remain in the gaseous phase and are recirculated back into the system (Jim Clark, n.d.).

Ammonia is often grouped into different categories or colours depending on how it is produced and the associated environmental impact. Figure 5 shows these types, classifying them based on production pathways and their corresponding labels.

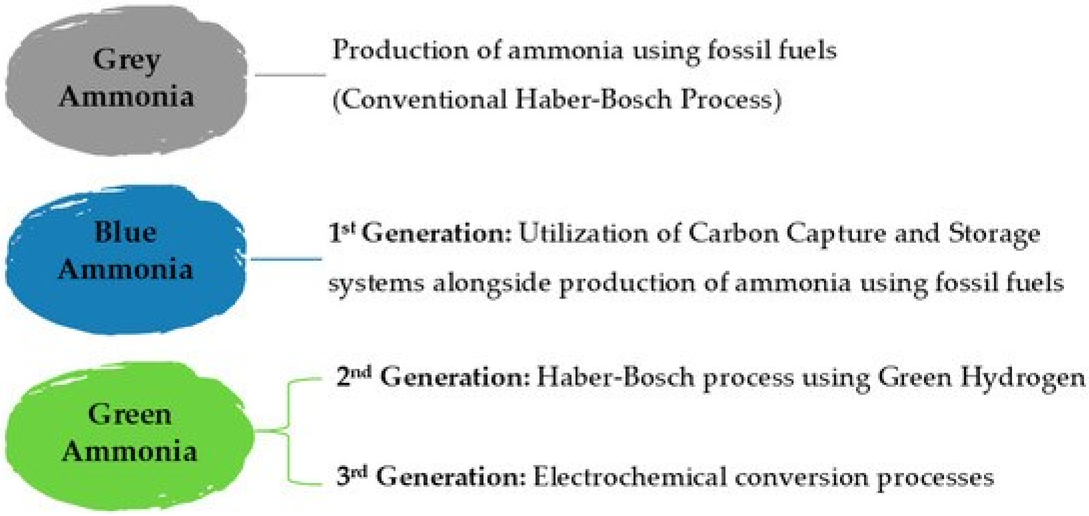


Figure 5. Categorization of ammonia based on the production process **(**Ribeiro & Santos, 2025).

Ammonia produced through the HB process using hydrogen derived from fossil fuels is referred to as grey ammonia. As a traditional method, it is not included in low-carbon generation classifications. When the HB process is combined with CCS, it becomes blue ammonia, categorized as a first-generation low-carbon option. However, its main limitation is the high cost of CCS, and it is generally considered a transitional solution (Ribeiro & Santos, 2025).

Green ammonia is produced using renewable energy sources and is considered carbon-free. It is commonly divided into second- and third-generation pathways. In second generation production, the conventional HB process is retained, but the hydrogen is obtained through water electrolysis powered by renewable electricity. Although this route is seen as a long-term solution, it involves high capital costs and relies on variable energy supply, which creates a need for effective energy storage systems (Ribeiro & Santos, 2025; Z. Wang et al., 2024).

Third-generation green ammonia eliminates the HB process entirely by producing ammonia through the electrochemical reduction of N_2, typically using water as the hydrogen source. This approach is still under development and includes methods such as direct N_2 reduction using electrocatalysts and indirect processes involving intermediates like lithium (Ribeiro & Santos, 2025).

Figure 6 presents an overview of the H_2 and NH_3 energy system, illustrating how hydrogen is produced from sources such as fossil fuels, coal gasification, and renewable energy (via electrolysis), then stored in different forms (compressed, liquid, or solid) or converted into ammonia through the HB process for easier storage and transport. It shows how these energy carriers are moved by road and maritime transport, and how they are ultimately used in applications like combustion engines and fuel cells for energy generation. The diagram also highlights key safety concerns, including risks of explosion, gas leakage, toxicity, and liquid spills, emphasizing the need for careful handling throughout the entire lifecycle.

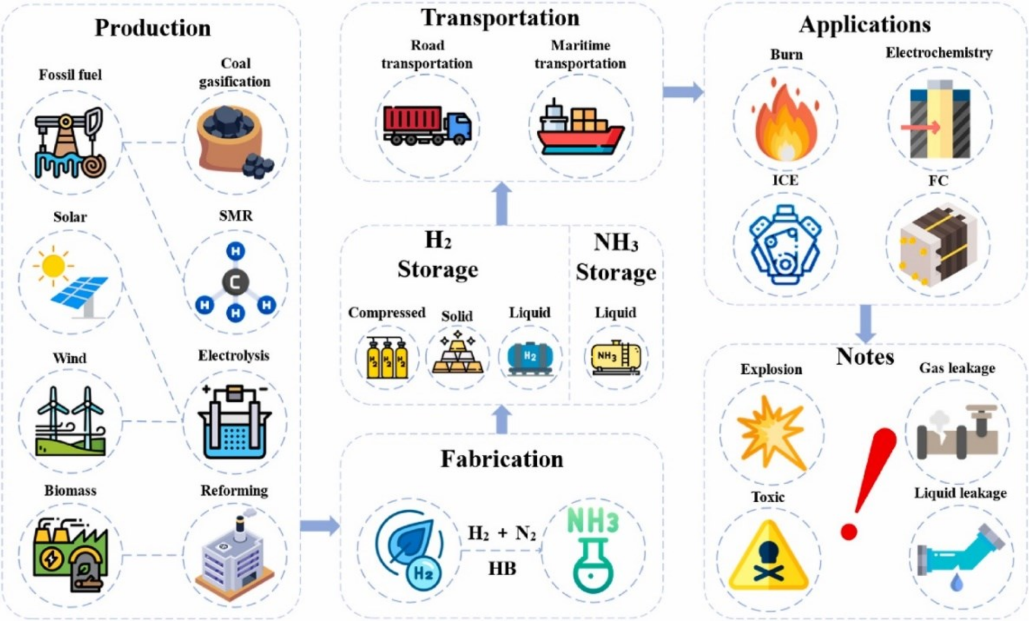


Figure 6. Production, storage, transportation, applications of Hydrogen and Ammonia alongside notes on their use(Z. Wang et al., 2024).

A wide range of experimental and theoretical studies has demonstrated that ammonia can be used as a fuel in internal combustion engines, including both spark-ignition and compression-ignition systems (Cheng et al., 2025). Using ammonia in ICE can be a cost-effective option, as it can be utilized with relatively minor engine modifications. In most cases, small amounts of hydrogen or diesel are used as pilot fuels to support ignition and improve combustion efficiency (Cheng et al., 2025; Duong & Kang, 2025).

In terms of storage, ammonia is more practical than hydrogen because it can be liquefied under less extreme conditions, allowing it to be stored either at low temperatures at atmospheric pressure or at moderate pressure at room temperature. Liquefied ammonia storage systems are less complex than those required for liquid hydrogen. As a result, ammonia offers a practical advantage for long-distance marine transport, particularly when compared with compressed or liquefied hydrogen (Cho et al., 2024; Jafar et al., 2024).

(Duong & Kang, 2025) note in their review study that beyond storage advantages, the physicochemical properties of ammonia are key to determining its viability as a marine fuel. Ammonia consists of one nitrogen atom bonded to three hydrogen atoms and contains about 17.6 wt% hydrogen, making it a useful hydrogen carrier for energy applications. Its lower heating value (LHV) is around 22.5 MJ/kg, which is significantly lower than that of conventional marine fuels, meaning larger quantities of fuel are needed to provide the same energy output. The main physicochemical properties influencing its use as a marine fuel are summarized in Table 2**.**

Table 2. Key physicochemical characteristics influencing ammonia's suitability as a marine fuel. Adapted from (Duong & Kang, 2025).

Property	**Value**	**Relevance for marine applications**
Chemical formula	NH_3	Carbon-free molecular structure
Hydrogen content	17.6 wt%	Enables use as hydrogen carrier

Property	**Value**	**Relevance for marine applications**
Lower heating value	~22.5 MJ/kg	Higher fuel mass required vs conventional fuels
Volumetric hydrogen density	~45% higher than liquid H_2	More compact hydrogen storage
Boiling point (1 bar)	−33.6 °C	Enables refrigerated liquid storage
Storage condition (ambient)	~8–10 bar at ~20 °C	Moderate pressure storage possible
Autoignition temperature	~651 °C	Long ignition delay in engines
Flammability limits (vol% in air)	~15–27%	Narrow flammability range
Laminar burning velocity	~0.07 m/s	Slow flame propagation
Minimum ignition energy	~680 mJ	Difficult ignition
Toxicity	High	Requires strict safety measures

Compared to liquid hydrogen, ammonia offers advantages as an onboard energy carrier due to its higher volumetric hydrogen density and less demanding storage conditions. These characteristics make ammonia a strong candidate for long-distance maritime transport, particularly when compared to fuels that require extreme cooling or high-pressure storage. For this reason, ammonia is often viewed not only as a fuel but also as a hydrogen carrier, owing to its more practical storage and transport properties relative to hydrogen (Duong & Kang, 2025; Li et al., 2025).

Even though ammonia is a potential alternative to fossil fuels it has its own challenges. Some of the challenges associated with its combustion in internal combustion engines are shown in Figure 7. The combustion properties of ammonia include high auto-ignition temperature, narrow flammability limits, low laminar burning velocity, and high minimum ignition energy. All these properties result in a long ignition delay and unstable combustion in internal combustion engines (Duong & Kang, 2025). These properties are the reasons behind the frequent use of pilot fuels and fuel blending concepts in ammonia-fueled engines. In addition, these properties make combustion and emission formation highly dependent on engine operating conditions (Tornatore et al., 2022).

Figure 7. Ammonia combustion challenges in ICEs (Pachiannan et al., 2025).

A key challenge in ammonia combustion is the formation of N_2-based emissions, particularly NOx and N_2O (Cheng et al., 2025). (Pachiannan et al., 2025) highlight that N_2O emissions are especially problematic due to their GWP, which is about 273 times higher than that of CO_2. It also notes that NO, NO_2, and N_2O are intermediate byproducts of ammonia combustion. (Cheng et al., 2025; Pachiannan et al., 2025) report that NOx emissions mainly arise from the N_2 contained within the fuel itself, which reacts during combustion.

In addition to this, ammonia slip also poses a major technical and environmental challenge when used in marine engines. It primarily results from the incomplete combustion under low temperatures or low load conditions and has been identified as a contributor to secondary N_2O production (Chavando et al., 2024; Cheng et al., 2025; Pachiannan et al., 2025). Thus, minimizing ammonia slip is essential. (Chavando et al., 2024) emphasize that, due to issues such as NOx emissions, N_2O formation, and ammonia slip, exhaust aftertreatment systems are essential for ammonia-fueled ICE. With techniques such as SCR, selective non-catalytic reduction (SNCR), and exhaust gas scrubbing identified as possible mitigation routes that can be employed in this context. A recent review (Li et al., 2025) also emphasize that, while ammonia combustion does not produce CO_2, NOx emissions remain a significant concern, highlighting the importance of effective emission control strategies when using ammonia as a marine fuel.

Beyond combustion related emissions, one of the most important issues is that ammonia is a toxic, corrosive, and moderately flammable substance (Cheliotis et al., 2021; Klerke et al., 2008; thanmano, 2024). Utilizing ammonia, especially onboard cracking demands for a multi-disciplinary safety strategy including engineering design, thermal and chemical risk management, spacing compartmentalization, automatic control and monitoring system, exhaust treatment, and regulatory coordination. With these holistic strategies, the shipping sector can utilize ammonia-fueled systems safely and pursue sustainable, zero-carbon shipping (Abubakirov et al., 2024; Cheliotis et al., 2021; Klerke et al., 2008; Popp & Müller, 2021; thanmano, 2024; Trivyza et al., 2021). In conclusion, ammonia exhibits great potential as a maritime fuel, however several challenges need to be addressed to fully realize the potential of this alternative fuel (Chavando et al., 2024).

2.1.4 LNG as a comparative fuel

LNG being the optimal transitional alternative fuel for maritime use is one of the most widely used alternative marine fuel, with LNG-powered vessels operating across number of segments and with well-established technologies such as fuel storage, bunkering, and propulsion systems. Given its well-developed application and availability of commercial infrastructure, LNG has been at the core of early stage of decarbonization and is well-utilized as a benchmark within assessments of alternative forms of fuel (Li et al., 2025). Figure 8 presents the sources, production pathways, and power applications of LNG.

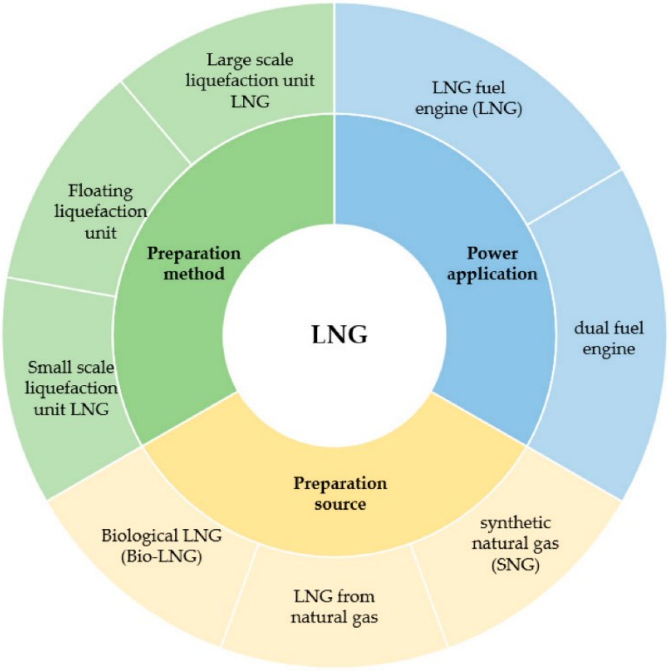


Figure 8. Production pathways, classifications, and power applications of LNG (Y. Wang et al., 2025a).

From an emissions perspective, LNG-powered dual-fuel engines can significantly reduce CO_2 emissions compared to conventional diesel engines, while also substantially lowering SO_x and PM. These advantages make LNG an attractive option for meeting air pollution regulations and GHG reduction targets (Li et al., 2025).

While LNG produces less CO_2 the critical issue associated with LNG as a marine fuel is the release of unburned CH_4, known as methane slip, during storage, transport or combustion. Methane slip is a key environmental drawback of LNG-fueled ships, with emission levels highly dependent on engine type and operating conditions. This phenomenon is particularly pronounced in low-pressure dual-fuel engines (Li et al., 2025;

Mohammadpour & Salehi, 2025). Given that CH_4 has a higher GWP, uncontrolled slip can partly or completely negate the CO_2 emissions benefits associated with it.

Consequently, LNG is regarded as a transitional and benchmark solution, as opposed to a long-term carbon-neutral solution towards decarbonization. While LNG's adoption stems from medium-term policy imperatives and is associated with measurable emission benefits compared to traditional fuels, it is still fettered by its reliance on fossil-based chemistry, problems of methane slip management and complex cryogenic infrastructure-related issues (Li et al., 2025; Mohammadpour & Salehi, 2025). Within this context, LNG represents a pragmatic and established benchmark in assessing new and long-term energy carriers such as ammonia.

2.2 LCA in maritime fuel studies

LCA is a standardized scientific approach used to evaluate the environmental impacts of a product, process, or service throughout its entire life cycle, from raw material extraction to production, distribution, use, and final disposal, as illustrated in Figure 9. It considers factors such as energy consumption, GHG emissions, water use, waste generation, and impacts on ecosystems and human health (ISO, 2006a).

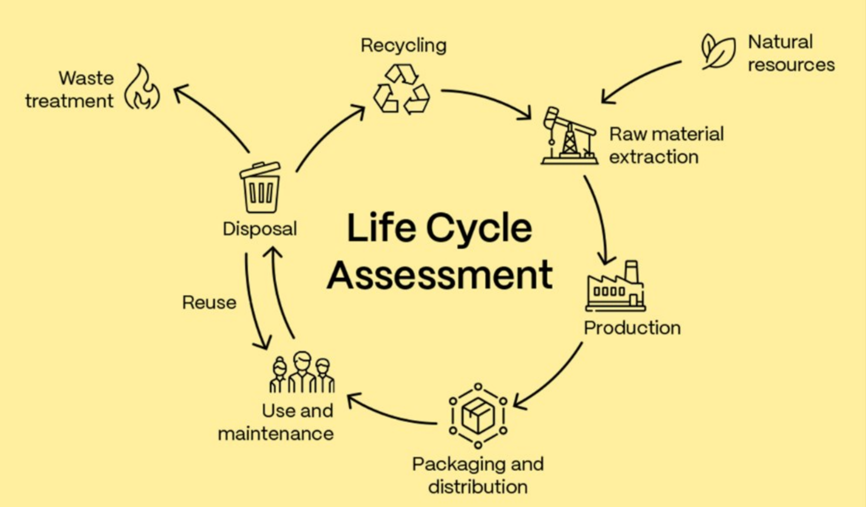


Figure 9. Scheme of Life Cycle Assessment (ecoinvent, n.d.).

LCA emerged in the late 1960s and early 1970s as basic analyses focused on comparing products and quantifying their energy consumption. (Liu et al., 2024). Between 1970 and 1990, it developed further but lacked clear methods and consistency. In the 1990s, LCA became more organized, with standard methods created by international groups like International Organization for Standardization (ISO) and the Society of Environmental Toxicology and Chemistry (SETAC). Since 2000, LCA has grown into a widely used tool for studying environmental impacts, and it continues to improve with new methods and broader applications (Guinée, n.d.; Liu et al., 2024). Figure 10 illustrates the evolution of LCA since 1990s.

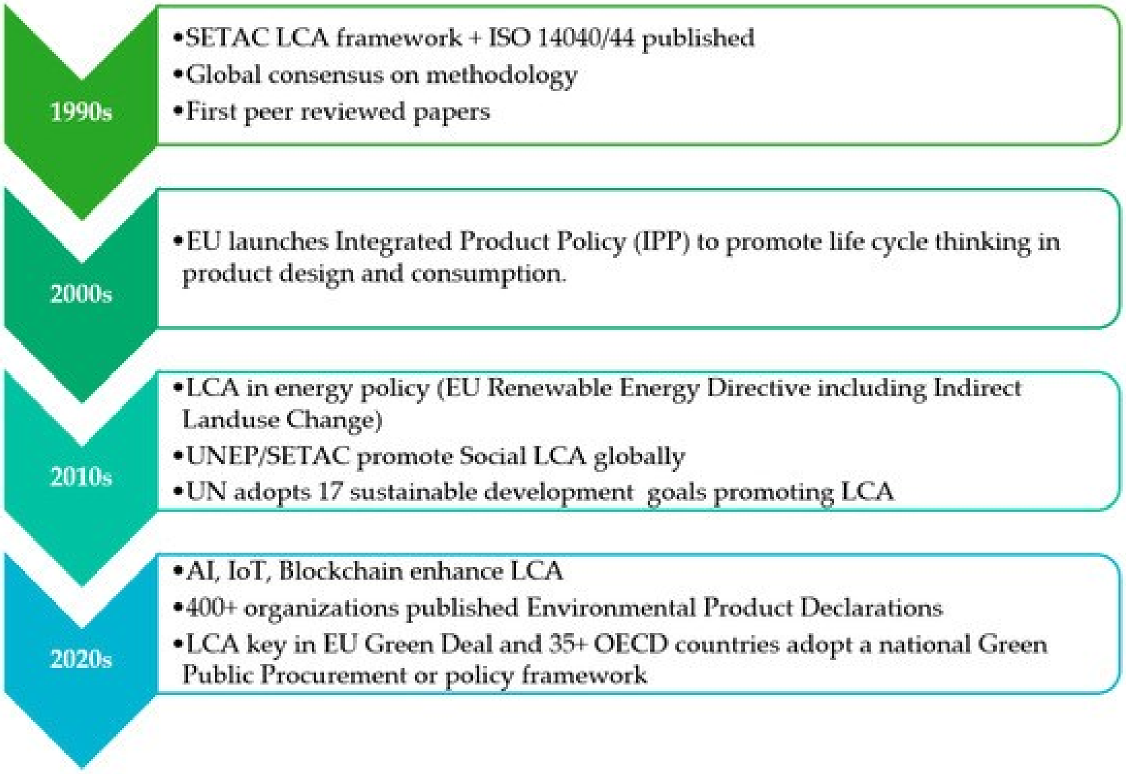


Figure 10. LCA development since 1990s (Kaynak et al., 2025).

According to ISO 14040 and 14044, LCA follows four key stages, as illustrated in Figure 11. The first step, defining goal and scope determines what product or system is being studied, why the study is done, and what is included or excluded. Second, inventory analysis involves compiling data on all inputs, such as materials and energy, and outputs, including emissions and waste, throughout the life cycle. The third stage, impact assessment, translates these flows into potential environmental impacts, such as greenhouse gas emissions or water use. The final step, interpretation, involves evaluating the results, identifying uncertainties or limitations, and drawing conclusions to support decision-making (Whittle et al., 2024).

Define the LCA's goal, scope, and boundaries, as well as which products to assess and the approach (e.g. cradle-to-grave).

Collect and organise all inputs (e.g. raw materials) and outputs (e.g., waste) throughout the product life cycles to create a Life Cycle Inventory (LCI) for accurate environmental impact assessment.

Convert data from the Life Cycle Inventory (LCI) into impact data using environmental impact categories.

Analyse the data and create conclusions, understand the study's limitations and create recommendations to use the LCA results to impact your business positively.

Figure 11. Four main steps of LCA (Root Sustainability, 2022).

In the maritime decarbonization context, LCA is commonly used to compare marine fuel pathways because it allows for a comprehensive assessment of emissions that extend beyond the use phase. The environmental impact assessment of alternative marine fuels cannot be based solely on operational or TTW emissions, as this approach considers the emissions impact of the fuel's combustion process only and could potentially ignore the large emissions impact of fuel production, processing, and distribution that occur in the upstream stages. The literature clearly shows that fuels that appear environment friendly at the exhaust stage could potentially have a different overall emissions impact when the upstream stages are also considered (B. A. Zincir & Arslanoglu, 2024). A recent study by (Nguyen et al., 2025) focusing on ammonia and hydrogen fuels, shows that, unlike conventional marine fuels, a large share of their total GHG emissions can originate from upstream production processes rather than the operational phase.

(Y. Wang et al., 2025b) mentions in their study that because of the above-mentioned limitations associated with the assessment of marine fuels, LCA has emerged as a widely accepted methodological approach to the assessment of marine fuels within a unified analytical framework. LCA enables assessment of environmental impacts associated with different stages of fuel lifecycle, thus enabling identification of trade-offs between operational characteristics and upstream emissions that cannot be assessed using exhaust-only-based assessments. (B. A. Zincir & Arslanoglu, 2024) highlight in their study that this is particularly important with alternative fuels such as ammonia or hydrogen, which may have low or zero CO_2 emissions during operation. Although the GHG emissions produced by ammonia and hydrogen are strongly dependent on production routes and energy sources used. (Nguyen et al., 2025) have also demonstrated that life cycle results for ammonia or hydrogen are particularly sensitive to assumptions made regarding production routes and electricity mix, resulting in significant variations in GHG emissions.

Existing literature has mainly used the system boundaries of TTW and well-to-wake (WTW). TTW focuses only on fuel use and emissions during ship operation, whereas WTW includes upstream stages such as fuel production, processing, and distribution (Y. Wang et al., 2025b). It has also been observed from the comparative LCA studies (Y. Wang et al., 2025b; B. A. Zincir & Arslanoglu, 2024) that the outcome of the study can differ significantly depending upon the system boundaries used, the fuel pathways chosen, and the assumptions made.

Critical reviews in literature (Roux et al., 2024) on maritime LCA studies further underscore the point that differences in system boundaries, data sources, emission factors, and underlying assumptions tend to dominate the results more than the differences in the fuels themselves, thereby impacting the comparability of results. (H. Lee et al., 2024) further underscore the point that the overall environmental performance of marine fuels can change significantly depending on the system boundaries applied to the analysis, even when the same fuels are considered in the analysis.

Thus, the literature on LCA of marine fuels underscores the importance of establishing clear system boundaries in a manner that is easily understandable to avoid any misleading results in the analysis of marine fuels. Within this context, LCA provides the methodological foundation of this thesis, which will help to evaluate the emissions from chosen marine fuels within clearly defined system boundaries and assumptions.

2.2.1 LCA frameworks in shipping

In maritime LCA research, fuel-related system boundaries are generally determined using three main frameworks: WTT, TTW, and WTW boundaries as shown in Figure 12. The WTT boundary includes emissions related to fuel production, processing, conversion, and supply to the ship, while the TTW boundary is only concerned with fuel-related emissions during ship operation and use. The WTW boundary combines both WTT and TTW boundaries, offering a complete picture of the total life cycle GHG emissions of a particular fuel (Gilbert et al., 2018).

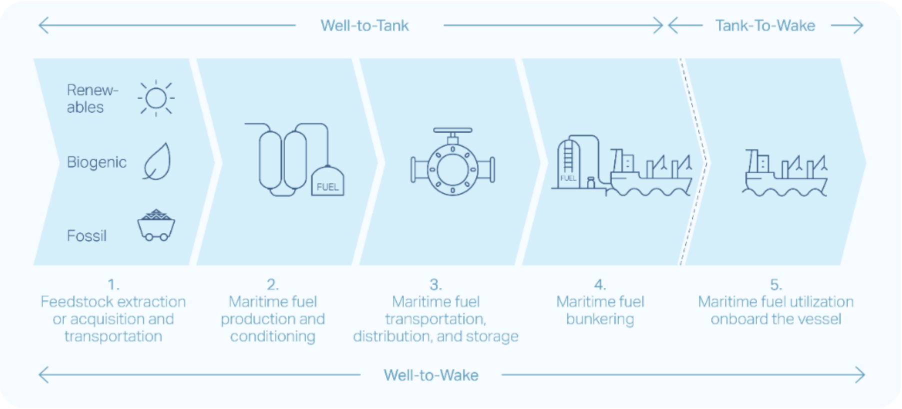


Figure 12. LCA system boundaries for maritime fuel (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023).

The selection of system boundaries depends on the study’s objectives, scope, and the specific environmental impacts being analysed. Although WTW boundaries are commonly used for fuel pathway analysis, TTW boundaries have also been frequently used to study fuel-related emissions during ship operation under realistic operating conditions (Y. Wang et al., 2025a).

This boundary-oriented concept is supported by internationally formalized regulatory methodology. For instance, in 2023, the IMO developed specific guidelines for assessing the life cycle GHG intensity of marine fuels, later updated in 2024, in which WTT, TTW, and WTW boundaries are explicitly defined as part of the international standard in assessing emissions from fuels in marine transportation. Under this boundary-oriented concept, TTW boundaries are designed to measure emissions from fuels used during ship operation, without considering upstream emissions, while WTT and WTW boundaries are designed to measure upstream and lifecycle emissions, respectively (Prussi, 2024).

2.2.2 Impact categories used in marine fuel LCAs

GHG emissions, usually quantified through GWP, are a major impact category for maritime LCA studies. This is because shipping is a contributor to global climate change and because LCA research is closely aligned with global policy initiatives aimed at reducing GHG emissions and mitigating global warming (Grigoriadis et al., 2024). Consequently, most LCA-based assessments of marine fuels prioritize GHG emissions when evaluating their environmental performance. Consistent with this framework, the IMO LCA guidelines require life cycle GHG performance to be reported as carbon intensity, expressed in grams of CO_2-equivalent per unit of energy, incorporating the global warming effects of CO_2 as well as other gases such as CH_4 and N_2O (Prussi, 2024).

Other emissions, such as NOx and fuel-specific pollutants are relevant for environmental impact assessments but generally play a limited role in most LCA-based assessments of shipping fuels. They are often addressed through additional analyses and therefore do not feature prominently as a factor for consideration in most LCA-based assessments of shipping fuels (Y. Wang et al., 2021). GWP is thus considered a major factor for consideration by most LCA-based assessments of shipping fuels.

2.2.3 Data sources and modeling approaches

Marine fuel LCAs involve the development of life cycle inventories using emission data from a combination of industry data, producer data, and published literature. Due to the inherent complexity of fuel supply chains and ship operations, several marine fuel LCAs have used emission factor-based methods for estimating fuel-related emissions within specific system boundaries for the purpose of assessing operational performance using the TTW method (Y. Wang et al., 2025b).

A range of commercial LCA tools and databases, including SimaPro, Boustead, GaBi, TEAM, GREET, ELCD, NREL, Ecoinvent, and the CLCD database, are commonly used in published studies on marine fuel LCAs (Herrmann & Moltesen, 2015). However, such methods are based on black-box-type calculations that may not provide transparency in emission modeling or assumption development. Several marine fuel LCAs highlight the significance of transparent calculation methods in defining system boundaries, functional units, and emission factors for LCAs thus enabling reproducibility and sensitivity analysis (Y. Wang et al., 2025b).

2.3 LCA studies on ammonia-fuelled ships

2.3.1 Combustion emissions of ammonia in marine engines

Comparative WTW LCA studies like (B. A. Zincir & Arslanoglu, 2024) have shown that, while ammonia is very attractive on a TTW basis because it does not emit CO_2 and SO_x during combustion, N_2O is the major GHG emitted during ammonia combustion, such that even a small formation rate can counteract the advantages of carbon-free exhaust operation.

Another recent comparative LCA study by (Tomos et al., 2024) compared hydrogen, ammonia, methanol, and bio-derived fuels with reference to the IMO's GHG emission reduction targets by 2050. The study shows that ammonia's GHG emissions depend significantly on N_2O emissions, given its high GWP of 297 kg CO_2-eq/kg. While ammonia has no emissions of CO_2 or SOx during combustion, both green and blue ammonia scenarios were shown to have a higher total life cycle GHG emissions than HFO in certain scenarios. Sensitivity analysis also reveals that a rise in N_2O formation by a certain percentage can increase total life cycle GHG emissions by up to 18%, making N_2O one of the most important parameters in ammonia LCA. Therefore, the study concludes that ammonia engine deployment should only be considered if N_2O formation can be tracked and minimized, pointing to a significant gap in current ammonia-fueled shipping LCA studies. This leads the discussion forward to the use of emission control.

2.3.2 Role of emission control systems

Even though the significance of N_2 based emissions in determining the environmental performance of ammonia is undeniable, the incorporation of emission control technologies is limited in the existing literature on LCA studies. In fact, a systematic review (Roux et al., 2024) on the LCA studies related to various types of maritime fuels revealed that only 23 out of 429 identified case studies specifically address the incorporation of emission abatement technologies, and SCR technology is considered in just 14 studies. Such limited incorporation of emission control technologies indicates that the results of LCA studies may not reflect the realistic scenario of the implementation of ammonia-fueled vessels in the future, considering the stringent regulations on emissions, and thus forms a gap in the existing LCA studies related to ammonia.

2.3.3 Reported environmental performance of ammonia

(Roux et al., 2024) conducted a systematic review of peer-reviewed LCA studies on marine fuels, selecting 43 articles published between 2011 and 2023 based on a defined criterion (see Table 3). Among these studies, only 24% examined alternative fuels such as hydrogen, methanol, and ammonia (Table 3). Among the studies focusing on alternative fuels, hydrogen was the most frequently investigated option, accounting for 33% of the sample, followed by methanol at 26%. In contrast, ammonia received comparatively less attention, with only 9 studies (21%). These findings highlight the relatively narrow scope of existing LCA research on ammonia, underscoring its lack of representation as a potential alternative fuel (see Table 4).

Table 3. Overview of reviewed LCA studies.

Category	Value
Total LCA studies reviewed	43
Publication period	2011 – Feb 2023
Studies on alternative fuels	24% of total

Table 4. Distribution of alternative fuel studies.

Fuel Type	Share of Alternative Fuel Studies	Approx. Number of Studies
Hydrogen	33%	~14
Methanol	26%	~11
Ammonia	21%	9

A broader review by (Y. Wang et al., 2025b) covering 64 alternative-fueled vessels and 12 fleet segments, shows that only 11 peer-reviewed studies have assessed the life cycle GHG emissions of ammonia fueled ships. Most of these studies focused on ammonia derived from fossil sources, with only limited analysis of green and blue ammonia for the WTT stage, even though these pathways are important for achieving long-term decarbonization. The findings of the studies have consistently indicated that while ammonia-fueled ships can reduce carbon footprint in the TTW stage due to carbon-free combustion, the overall environmental performance remains strongly dependent on the upstream production pathways. Fossil-based ammonia pathways have a significantly higher WTT carbon footprint compared to conventional marine fuels.

The comparative LCA study by (B. A. Zincir & Arsanoglu, 2024), where ammonia was compared to LNG, hydrogen, methanol, and conventional fuels within a WTW life cycle framework and an ocean tanker model using GREET 2022 findings indicate that ammonia performs well across multiple non-climate impact categories, including acidification, PM, nutrient pollution in both marine and land ecosystems, and the formation of ground-level ozone. Ammonia, however, has one of the worst climate change impact scores when produced from natural gas, mainly due to its feedstock and fuel conversion emissions, where N_2O has a dominant contribution to its GHG emissions.

More recent fuel-specific LCAs have shown that renewable ammonia can have a significant impact on improving its environmental performance. For instance, a WTW assessment carried out by (Tripathi et al., 2026) shows that wind-based ammonia production can achieve a significant reduction in GHG emissions, at 72-77% lower than the HFO baseline, thus meeting the IMO 2040 target of at least a 70% GHG reduction, while fossil-based ammonia showed significantly higher emissions. In a similar assessment (H. Lee et al., 2024) carried out on nine alternative fuel pathways, e-ammonia was shown to achieve an approximate 86.6% GHG reduction compared to conventional marine fuels, making it one of the most environmentally friendly options alongside biomass-based Fischer-Tropsch diesel and e-methanol. Moreover, the same study shows that when life cycle carbon price scenarios are considered, e-ammonia becomes a cost-competitive option compared to LNG and HFO, thus reiterating its potential use as a solution to the decarbonization problem rather than a transitional fuel.

Overall, the available literature suggests that ammonia has significant potential for reducing operational carbon emissions based on its carbon-free combustion properties, although its life cycle environmental impacts are highly variable and sensitive to assumptions and methods used for analysis, as well as its production processes and treatment of N_2 based emissions. Systematic reviews have consistently demonstrated that ammonia is substantially underrepresented in maritime LCA literature compared to other alternative fuels, with only a small number of peer-reviewed studies investigating its life cycle impacts and even fewer studies focusing on green or blue ammonia pathways, which are crucial for long-term decarbonization.

Furthermore, studies indicate that ammonia produced from fossil sources can generate WTT emissions comparable to or higher than those of conventional marine fuels. In contrast, ammonia derived from renewable electricity shows better environmental performance and has the potential to meet the IMO’s 2040 and 2050 emission reduction targets.

At the same time, literature has also been characterized by a lack of and inconsistent treatment of key factors such as N_2O emissions, effects of pollutants beyond those related to climate change, and emission control technologies, with many LCA studies using a simplistic representation of ammonia engine operation. These are key factors that have resulted in limitations to the comparability and robustness of current findings and have created a need for transparent and scenario-based LCA that consider factors related to ammonia production, N_2 based emissions, and emission control technologies for ammonia as a marine fuel.

2.4 LCA studies on LNG and dual-fuel marine engines

2.4.1 LNG combustion emissions

Life cycle studies of LNG-powered ships show that CO_2 emissions are lower during the TTW phase, although the level of reduction depends on the engine technology used. This is largely due to the high hydrogen-to-carbon ratio of natural gas, which is mainly composed of CH_4, making up about 90–95% of LNG by volume (Zou & Yang, 2023). Several studies stress the fact that the climate impacts of LNG are heavily dependent upon the combustion characteristics, especially methane slip, which could offset the benefits of LNG as a marine fuel (Y. Wang et al., 2025b).

CH_4 emissions occur during the operation of the engine and it is noteworthy that the emission of CH_4 depends on the engine type, thereby making methane slip one of the most critical areas of uncertainty in the TTW assessment of LNG. During the operation of the engine, methane slips can occur due to incomplete combustion and engine cylinder component gaps. It is critical to note that the occurrence of methane slips happens during the flame-out mode of operation (Zou & Yang, 2023).

CH_4 has a GWP of 82.5 times higher than that of CO_2 over a 20-year time scale and 29.8 times higher than that of CO_2 (Intergovernmental Panel on Climate Change (IPCC), 2023). Which means that even the small amounts of methane emissions can have a disproportionately large impact on climate change. This is especially crucial in the case of LNG-powered ships where unburned methane, also known as methane slip, occurs during engine operation. Whereas LNG engines have the capacity to make significant decreases in CO_2 emissions, the occurrence of methane slip can negate these advantages. Consequently, the net GHG savings of LNG-powered ships might range widely, between substantial savings and instances where the net effect on climate may be higher than with traditional diesel fuels (Y. Wang et al., 2025b; Zou & Yang, 2023).

Although the N_2O emissions are typically lower than CH_4 emissions, they are not insignificant and are not consistently accounted for in LNG LCAs. The relative lack of attention to N_2O emissions also adds to the inconsistencies in the reported TTW GHG performance of LNG-fueled ships, especially in studies that focus on CO_2 and CH_4 emissions but ignore secondary GHGs such as N_2O (Chalaris et al., 2025).

2.4.2 Dual-fuel engine operation

Most of the existing LNG-fueled vessels operate using dual-fuel engine modes, in which the combustion of the natural gas is supplemented with the use of a liquid fuel for the purpose of maintaining the stability of the ignition process. Dual-fuel engines with the use of a pilot fuel or compression ignition modes have been the most popular mode of propulsion for LNG-fueled vessels, which is considered to be technologically mature with economic equivalence to traditional diesel engines for the purpose of widespread application in the maritime sector (Xing et al., 2021; Zou & Yang, 2023). The results of the life cycle studies have shown that the dual-fuel mode of the LNG engine has a significant influence on the environmental impact in terms of the CO_2 emissions as well as methane slip (Maydison et al., 2024).

Moreover, comparative analyses indicate that some dual-fuel engine technologies can provide substantial cuts in GHG emissions, while other technologies show little or even negative climate benefits due to high CH_4 emissions related to the fuel combustion strategy (Y. Wang et al., 2025b). The fact that the pilot fuel can be an effective means for cutting emissions of CO_2, NOx, SO_x, and PM in comparison to traditional marine fuels also creates a degree of additional sensitivity to the risks of combustion inefficiencies and methane slips during operation (Cucinotta et al., 2021; Xing et al., 2021; Zou & Yang, 2023).

The widespread application of pilot fuel in LNG dual-fuel engines provides a critical methodological reference for assessing the emerging dual-fuel concepts. In particular, the LNG-related LCAs can be used for assessing the pilot fuel-related implications for operational emissions, thus facilitating the comparability of LNG dual-fuel and ammonia dual-fuel systems in TTW LCAs (H. Wang et al., 2025).

2.5 Comparative studies of ammonia and LNG in shipping

The comparative LCA studies that have investigated ammonia and LNG as marine fuels have yielded highly divergent results, indicating considerable variability in methodology rather than any consensus on relative performance. Although LNG is often evaluated as a transitionary benchmark fuel and ammonia as a future zero-carbon alternative, comparisons between the two fuels indicate a strong dependence on system boundaries, emission factors and engine technology assumptions (Roux et al., 2024; Y. Wang et al., 2025b).

Some studies have indicated that LNG is preferable to ammonia in TTW comparisons because of lower operational GHG emissions when methane slip is minimized and engine combustion efficiency is high (Li et al., 2025; Mohammadpour & Salehi, 2025). On the other hand, a greater or more uncertain TTW GWP for ammonia is often reported when N_2O formation and ammonia slip are explicitly included, particularly in studies that use conservative emission factors or assume low effectiveness of exhaust after-treatment systems (Cheng et al., 2025; Pachiannan et al., 2025). These findings have led some researchers to argue that the climate mitigation potential of ammonia depends more on combustion conditions and the effectiveness of emission control systems than on the fuel's inherent properties.

On the contrary, comparative studies that also account for upstream emissions often invert this order. For instance, the GHG reduction potential of LNG fuel diminishes in full life cycle analyses when CH_4 emissions from fuel extraction, processing, and distribution are combined with methane slip during engine operation, potentially offsetting or even surpassing the reduction of CO_2 observed during exhaust stage evaluation (Y. Wang et al., 2025b; B. A. Zincir & Arslanoglu, 2024). In contrast, ammonia derived from renewable electricity routes consistently exhibits significantly lower WTW GHG emissions, under the assumption of green production pathways and adequate control of N_2 based emissions (Nguyen et al., 2025; Roux et al., 2024).

Another important source of inconsistency in the results obtained through comparative studies is the way emission factors and other pollutants, aside from CO_2, are being treated. The methane slip assumptions used in LNG engine performance are highly variable across the literature and are often scenario-dependent, while the emission of N_2O from ammonia combustion is often reported, neglected, or simplified through the use of fixed emission factors, which are highly sensitive to engine load, temperatures, and after-treatment performance (Cheng et al., 2025; Roux et al., 2024). Hence, small variations in emission factors can cause large variations in the calculated GWP of the fuels.

The choice of the system boundaries is also one aspect that causes inconsistency in the results obtained from the studies conducted to compare the performance of the two fuels. Studies using tank-to-wake boundaries tend to focus on operational emissions and engine performance, often favoring LNG as the preferred fuel. In contrast, studies using well-to-wake boundaries emphasize the significant impact of fuel production, often favoring green ammonia instead (Y. Wang et al., 2025a; B. A. Zincir & Arslanoglu, 2024). The lack of standardized definitions for boundary conditions limits the ability to compare the results obtained from different studies and complicates cross-fuel comparisons.

An additional area of divergence involves engine technology assumptions. Comparative studies often use different engine types, pilot fuel fractions, and emission control strategies, even when ostensibly comparing the same fuels. As both LNG and ammonia fuels are typically used in dual-fuel engines that rely on pilot fuel fraction, variations in pilot fuel share and combustion strategy create further uncertainty in TTW evaluations (Cheng et al., 2025; Li et al., 2025).

The existing literature clearly reveals that comparative LCA results for ammonia and LNG are highly inconsistent and are influenced more by methodology than by any fuel properties. Differences in emission factor selection, system boundary definition, and engine assumptions are some of the major factors influencing comparative LCA results. Such inconsistencies in existing literature are motivating factors for this investigation, where an attempt is made to comparatively assess ammonia and LNG through a transparent methodology with consistent operational assumptions for a realistic marine scenario.

2.6 Methodological variations and key challenges

2.6.1 Functional units used

The selection of functional units has been recognized as one of the most important methodological decisions in LCA studies related to marine fuels, as it has a direct impact on their comparability. Functional units are usually used to describe the main purpose of the system studied, as well as to allow for a comparison between different technologies and fuel pathways (Roux et al., 2024). Based on the available literature, it has been noticed that functional units are not used in a uniform manner in different stages of the fuel life cycle, specifically between the upstream and operational phases.

For the WTT phase, it is noted that for maritime LCA studies, there is a consistent functional unit applied, as expressed in grams of CO_2 equivalent per unit of energy content of the fuel, i.e., gCO_2e/MJfuel. This allows for standardized comparisons of the upstream production pathways for the fuel, which is consistent with international methodological guidelines for reporting carbon intensity of fuels (Y. Wang et al., 2025a).

Contrarily, considerable variability is observed in the functional units used for the TTW phase of the analysis. The existing studies on the emission analysis of ships report the following functional units: gCO_2e/MJ of shaft work, gCO_2e per kilowatt-hour of engine output, gCO_2e per tonne-nautical mile, gCO_2e/MJfuel, and tonnes of CO_2-equivalent per tonne of fuel consumed. This variance is due to the nature of research focus, type of vessels, their operation profiles, and available data, but it presents challenges in comparison of the reported operational emissions (Roux et al., 2024; Y. Wang et al., 2025a).

(Roux et al., 2024) also note that several functional units based on energy consumption or fuel mass do not sufficiently represent the actual transport function of a vessel. This is because different types of fuel have different energy densities, and thus different onboard storage requirements, which can reduce the amount of cargo or passengers carried and, therefore, affect the number of voyages required to transport the same amount of transport service. This issue is particularly important for alternative marine fuels such as LNG, hydrogen, methanol, and ammonia, which have lower energy density than conventional fuels and therefore require more onboard storage, creating noticeable space and efficiency constraints.

In general, the current state of research shows that the issue of inconsistent functional unit selection is a significant methodological issue in maritime fuel LCA studies, which directly impacts the comparability of results. This further underlines the importance of consistent functional unit selection that is justified and aligned with the specific purpose of the study, especially when comparing alternative fuels with significantly different energy densities.

2.6.2 System boundary choices

Across maritime LCA research, the selection of the system boundary has been consistently found to be a key factor that dominates the results. Existing literature categorizes three system boundaries WTT, TTW, and WTW. WTT includes the processes in the upstream stages of the lifecycle of the fuel or energy carrier, including extraction, processing, production, handling, transportation, and distribution, as well as the emissions produced in the process regardless of where the fuel is ultimately used. TTW phase includes the use phase of the fuel, including the emissions produced in the process of combustion of the fuel irrespective of the point of production or distribution of the fuel or energy carrier. WTW includes both the WTT and TTW approaches (Prussi, 2024; Y. Wang et al., 2025a). The comparative LCA data also show that significant variations in outcomes can be expected depending on system boundaries used for analysis, even when comparing similar fuels, since this ultimately decides whether fuel pathway emissions are included or excluded in analysis (H. Lee et al., 2024; Y. Wang et al., 2025a; B. A. Zincir & Arslanoglu, 2024).

This sensitivity to boundaries is particularly apparent in comparative analyses of LNG and ammonia. Research using TTW boundaries tends to focus on operational emissions and engine performance, potentially favoring LNG if methane slip is reduced and engine combustion efficiency is high(Li et al., 2025; Mohammadpour & Salehi, 2025). Conversely, research using WTW boundaries tends to reverse findings by accounting for upstream emissions, in which case LNG performance may degrade when CH_4 emissions from production and distribution is also considered along carbon emission and methane slip during TTW phase (Y. Wang et al., 2025a; B. A. Zincir & Arslanoglu, 2024). Similarly, ammonia tends to be beneficial within TTW boundaries owing to carbon-free combustion properties, while WTW results are largely affected by fuel production pathways, where fossil-based ammonia tends to show substantially higher emissions compared to renewable electricity-based ammonia (Roux et al., 2024; Y. Wang et al., 2025a). Consequently, the literature emphasizes that the definition of boundaries is not just a technical aspect, but rather a crucial factor that determines whether the fuels are found to be environmentally favorable or unfavorable in the LCA results (Y. Wang et al., 2025a; B. A. Zincir & Arslanoglu, 2024).

The need for transparent and well-communicated boundary choices is emphasized in critical reviews of maritime LCAs. Systematic and comparative reviews state that the differences in system boundaries, data collection, emission factors, and assumptions tend to have a greater impact on the results than the fuel differences themselves, which directly affects the results of the findings (H. Lee et al., 2024; Roux et al., 2024). Therefore, it can be concluded from the literature that well-defined boundaries are necessary to prevent misinterpretations, especially when comparing fuels with significant differences in upstream and operational emission profiles (Y. Wang et al., 2025a; B. A. Zincir & Arslanoglu, 2024).

2.6.3 Treatment of nitrogen-based emissions

A recurring problem in the methodological approach of ammonia-related maritime LCAs is the inconsistent treatment of N_2 based emissions, notably the formation of N_2O and ammonia slip. Several studies show that ammonia is seen as an attractive option from a TTW perspective, as it emits no CO_2 or SO_x during combustion, while at the same time, N_2O is seen as a key GHG emitted during ammonia combustion, where even small formation rates can negate the benefits of carbon-free exhaust emissions (B. A. Zincir & Arslanoglu, 2024). The results of comparative LCA studies show that the GHG balance of ammonia can be highly sensitive to the formation of N_2O, where sensitivity analysis has shown that changes in N_2O formation can have a significant effect on the total life cycle

GHG emissions (Tomos et al., 2024). In addition, the literature on the behavior of ammonia engines points out that ammonia slip can arise due to imperfect combustion at low temperatures or low load conditions, which has been identified as a source of secondary N_2O formation, thus supporting the importance of accounting for these emissions in the assessment of ammonia as a marine fuel (Chavando et al., 2024; Cheng et al., 2025; Pachiannan et al., 2025).

Despite the known importance of N_2 based emissions, existing LCA research has not consistently addressed these pollutants. The overall body of research provides a basis for comparison, which suggests that TTW GWP for ammonia tends to be higher or less certain if N_2O formation and ammonia slip are considered, especially where conservative emission factor values are applied or where limited effectiveness of emission abatement measures are assumed (Cheng et al., 2025; Pachiannan et al., 2025). Other research has been cited as failing to consider or simplistically treating N_2O emissions using fixed emission factors, where N_2O emissions are known to vary with engine load, temperature, and after-treatment conditions, resulting in significant variability (Cheng et al., 2025; Roux et al., 2024). This variability is also seen in the reviews, which state that the emissions of pollutants, excluding the GWP, are often not extensively discussed, and these important factors affecting ammonia performance are not consistently incorporated.

Another closely related limitation of existing methodological approaches is that they do not adequately account for emission control technologies. An existing systematic review (Roux et al., 2024) of maritime fuel LCAs reveals that only a small proportion of existing case studies explicitly consider emission abatement technologies with SCR appearing in only a limited proportion of these. The limited consideration of emission control technologies within existing LCAs raise concerns about the reliability of the existing ammonia related LCA results. This reinforces the need for N_2 based emissions and their mitigation to be addressed explicitly.

2.7 Summary of literature gaps

The reviewed literature clearly shows that, despite the growing focus on alternative marine fuels, studies focused on LCA of these alternative fuels are limited and among these peer-reviewed maritime LCA studies ammonia is significantly underrepresented. Systemic and broad review studies clearly indicate that only a small number of peer-reviewed LCA studies assess the different pathways of ammonia as a marine fuel, especially in comparison to hydrogen and methanol fuels. This limits the reliability and comparability of results regarding its environmental performance in maritime sector (Roux et al., 2024; Y. Wang et al., 2025a).

A closely related concern is the lack of LCA studies covering the inclusion of green and blue ammonia as alternative marine fuel. In fact, existing research is largely centred on fossil-derived ammonia, while analyses of green ammonia and its renewable production pathways remain scarce (Roux et al., 2024; Y. Wang et al., 2025a). This limitation restricts the ability of existing studies to evaluate ammonia's role in future maritime decarbonization.

The literature also indicates a high level of inconsistency in comparative LCA results between ammonia and LNG, with results often cited as being divergent and more a reflection of methodological choices than actual fuel characteristics. A number of comparative LCA studies have consistently shown that results on relative life cycle climate performance vary depending on the defined system boundaries, selected emission factors, functional units, vessel types, operational profiles, and engine efficiencies preventing a clear conclusion on which fuel performs better from a life cycle perspective (Roux et al., 2024).

One of the major factors that contribute to this disparity is the great impact that the selection of system boundaries has on the results. TTW boundary studies tend to focus on operational emissions and engine performance, while WTT studies tend to focus on the significant impact that fuel production has. The absence of standardized boundaries makes it difficult to compare results across studies and across fuels hence complicating policy and decision making (Y. Wang et al., 2025a; B. A. Zincir & Arslanoglu, 2024).

Likewise, the selection of functional units across studies is inconsistent, especially for the TTW phase calculation. The selection of functional units for the WTT calculation is often energy-based, expressed in terms of gCO_2e per MJ of fuel, while the functional units for the TTW calculation vary widely, including units related to fuel input, engine output, and transport work. This has been widely acknowledged as a limitation of the methodology, which does not allow for the comparison of emissions from vessels, routes, and fuels (Roux et al., 2024; Y. Wang et al., 2025a).

For LNG, methane slip is identified as a major uncertainty driver for TTW performance, with reported outcomes ranging from significant emission reductions to scenarios where LNG performs worse than diesel once CH_4 emissions are considered in full detail. For ammonia, N_2 based emissions are often ignored or addressed in an inconsistent and often simplistic manner (Y. Wang et al., 2025a; Zou & Yang, 2023). N_2O and ammonia slip are reported as outcome-defining parameters due to their high GWP, though many models either fail to account for such emissions or use fixed emission factor approaches to represent them, rather than accounting for their sensitivity to engine load, combustion temperature, or after-treatment performance (Cheng et al., 2025; Roux et al., 2024).

In addition, the literature emphasizes the lack of consideration of emission reduction technologies, with a particular reference to SCR technologies. Systematic review by (Roux et al., 2024) indicate that only a few LCA studies on maritime fuels consider emission control technologies in their study, with only a few studies including the consideration of the SCR technology, which is essential in the realistic assessment of the LCA studies, given the increasingly stringent regulations.

The other significant gap identified is the differences in the engine and operational assumptions, which vary significantly in the comparative studies. The differences in the types of engines, pilot fuel fractions, and combustion modes, as well as emission control handling, are notable, even where the fuels considered are the same, further reducing the comparability of the TTW studies (Cheng et al., 2025; Li et al., 2025).

Lastly, the reviewed literature suggests that there is a transparency gap regarding modeling approaches and data handling. For instance, several LCAs have used black box modeling tools and aggregated emission factors obscuring assumptions and limiting reproducibility. Reviews have also emphasized the need for transparent calculation methods that can accommodate sensitivity analysis and interpretation of results. Reviews have also emphasized the need for transparent calculation methods that can accommodate sensitivity analysis and interpretation of results (Y. Wang et al., 2025b). This is closely related to the need for scenario-based handling of uncertainty, as it has been demonstrated that variability regarding methane slip, N_2O formation, emission factors, aftertreatment, and assumptions used for engine are dominant result drivers (Roux et al., 2024; Y. Wang et al., 2025a).

Collectively, the reviewed literature has shown that the current state of comparative LCA studies is limited by a lack of methodological consistency, pollutant-level emission representation, and operational realism. To address these limitations, the current study covers a transparent TTW LCA for a real-world offshore platform supply vessel (PSV), comparing green ammonia and LNG as alternative marine fuels under clearly defined operating conditions.

3 Methodology

This chapter outlines the methodology used to conduct a comparative LCA of green ammonia and LNG as marine fuel options. The analysis follows the standard LCA structure defined by ISO under ISO 14040 and 14044. Which consists of goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation (ISO, 2006a, 2006b). Figure 13 illustrates the overall methodological approach used in this study.

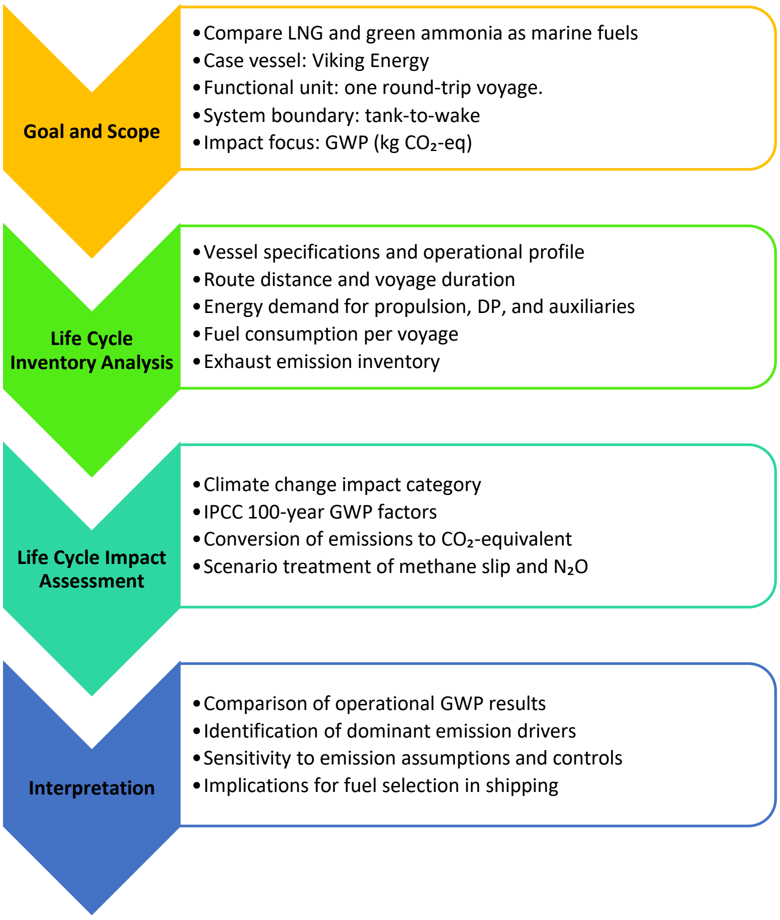


Figure 13. LCA framework used in this study, based on ISO 14040/14044 and adapted to a tank-to-wake comparison of green ammonia and LNG as marine fuels.

3.1 Goal and Scope Definition

The aim of this LCA is to quantify and compare the operational GHG emissions of green ammonia and LNG as marine fuel options. The assessment evaluates their environmental performance under realistic operating conditions while applying a consistent methodology to avoid discrepancies seen in earlier studies. The study considers a specific vessel's operational conditions. It is a real-world PSV, Viking Energy (Figure 14), deployed by Equinor in the Norwegian continental region. The choice of this vessel is based on its suitability for dual-fueled operation, the availability of technical and operational data, and relevance to offshore supply activities where repeated shuttle voyages are representative of normal operation.

Figure 14. Viking Energy platform supply vessel (Equinor, 2024).

The functional unit for the assessment is defined as one complete round-trip journey between the Mongstad onshore supply base (see Figure 17) and the Oseberg A offshore platform (see Figure 18) and then returning to Mongstad. The GHG emissions are quantified and reported on a per voyage basis in kilograms of CO_2 equivalent (kg CO_2e). The functional unit for the assessment is based on the real-world scenario of PSV operations and allows for direct comparison of fuel performance under identical conditions.

The selected system boundary for the assessment is TTW. The TTW phase includes fuel combustion and fuel consumption during vessel operation, including the impact of the pilot fuel and exhaust after-treatment effects where applicable. The analysis does not account for emissions arising from upstream activities, including fuel production, processing, and distribution, as these fall outside the defined system boundary. The selection of the system boundary is consistent with the IMO definition of TTW emissions and the focus of the study.

By defining a consistent functional unit, system boundary, and operational profile, this study seeks to offer a transparent and comparable assessment of the TTW phase GWP of green ammonia and LNG as alternative marine fuels when used in a dual-fuel marine engine on a representative offshore supply vessel route.

3.2 Data collection and setup workflow for the LCA calculator

3.2.1 Initial case vessel screening

Before the final case vessel was selected, technical and operational information for four different vessels was obtained from published literature as shown in **Table 5.** The primary purpose of the literature reviewed was to screen the information for the final case vessel selection, via assessing the availability of data, technical information, and compatibility for the LCA modeling for the different vessels. At this stage, Viking Energy was not considered because the focus was on vessels that were previously reported in LCA studies or fuel comparison studies. This initial screening gave an indication of the general structure and limitations of the data available in the literature.

Table 5. Technical and operational specifications of the initially screened vessels.

Parameter	**T/S Segero (Source 1)**	**Demonstrator Vessel (Source 2)**	**VLCC (Source 3)**	**General Cargo Ship (Source 4)**
Vessel Name / Type	T/S Segero (Training Ship)	Demonstrator: Multi-purpose Dry-Cargo Heavy Lift Vessel	Very Large Crude Carrier (VLCC)	General Cargo Vessel
Length Overall (LOA)	133 m	193.9 m		128 m

Parameter	**T/S Segero (Source 1)**	**Demonstrator Vessel (Source 2)**	**VLCC (Source 3)**	**General Cargo Ship (Source 4)**
Length Between Perpendiculars (LBP)	120 m	-	333.0 m	-
Breadth (B)	19.40 m	28.2 m	60.0 m	18 m
Depth (D)	8.40 m	15.6 m	30.0 m	9.7 m
Draught (T)	6.40 m	11.2 m	20.5 m (Design), 22.0 m (Scantling)	9.7 m
Gross Tonnage (GT)	9196 GT	-	-	6,177
Deadweight	-	31,000 tons	310,000 tons	10,300 tons
Cargo Capacity	-	39,700 m³	-	-
Container Capacity	-	2019 TEU	-	-
Main Engine Model	MAN B&W S35ME-C9.7-GI	-	-	S.X.D. Daihatsu 8DKM-28
Engine Type	Dual-Fuel, Low-Speed	-	Low-Speed, Two-Stroke Diesel	-
Main Engine Power (SMCR)	6960 kW	10,458 kW	22,000 kW	2,500 kW
Engine RPM	167 RPM	120 RPM	-	750 RPM
Service Speed	17.66 knots	16.8 knots	14.5 knots (service), 13.5 knots (eco)	12.3 knots

Parameter	**T/S Segero (Source 1)**	**Demonstrator Vessel (Source 2)**	**VLCC (Source 3)**	**General Cargo Ship (Source 4)**
Operational Range	12,715 nautical miles	15,000 nautical miles	-	-
Complement (Crew/Personnel)	239 persons	-	-	-
Fuel Type (Before Retrofit)	Marine Diesel Oil (MDO)	-	Marine Gas Oil (MGO)	-
Fuel Type (After Retrofit)	Liquefied Natural Gas (LNG)	Green Ammonia (assumed)	Ammonia, LNG, Methanol (for comparison)	-
Tank Type	Type-C	-	-	-
Tank Capacity Variants	20%, 30%, 40% replacement scenarios	-	-	-
Years Remaining in Service	-	17 years (as of 2024)	-	-
Net Tonnage (NRT)	-	-	-	3,680
Diesel Generators	-	-	-	2 × 220 kW @ 800 RPM
Fuel Type (Before Retrofit)	-	-	-	HFO/MDO
Fuel Tank Capacity	-	-	-	363 m^3
Year Built / Keel Laid	-	-	-	2004

Parameter	**T/S Segero (Source 1)**	**Demonstrator Vessel (Source 2)**	**VLCC (Source 3)**	**General Cargo Ship (Source 4)**
Data Source	Maydison et al., 2024	H. Wang et al., 2025	Huang et al., 2022	B. Zincir, 2022

3.2.2 Final Case Vessel Selection: Viking Energy

Viking Energy was selected as a case vessel because it was relevant to the offshore supply operations, had readily available technical specifications and was appropriate for the dual-fuel life cycle comparison. Choosing a real operating vessel enabled the study to concentrate on a real-life example.

3.2.3 Technical specification compilation for Viking Energy

To prepare the LCA model, the technical specifications of Viking Energy as shown in **Table 6** necessary for conducting life cycle assessment were collected and compiled from the publicly available sources (Wärtsilä, n.d.-a, n.d.-b, 2024). Which included the hull characteristics, capacity, as well as the propulsion/power generation arrangement, type of engine, rated power, and thrusters, among other characteristics. The vessel is fitted with four Wärtsilä 6L32DF dual-fuel engine generators, each with a capacity to produce 2010 kW of electricity to power the electric propulsion, dynamic positioning (DP), and onboard auxiliary loads. This total installed power provided by these 4 engines forms the basis for total estimated operational energy demand during ship cruising, maneuvering, and DP modes in the LCA modelling.

Table 6. Technical and operational specifications of Viking Energy.

Category	Value	Unit	Reference
Route Start	Mongstad: Latitude: 60.8167 N Longitude: 5.0333 E	-	(Equinor, n.d.-a)
Route End	Oseberg A: Latitude: 60.4919 N Longitude: 2.8273 E	-	(Norwegian Offshore Directorate, n.d.)
Distance Between Mongstad and Oseberg A	~68	NM	**Figure 16**
Round-trip Distance	~136	NM	**Figure 16**
Average Speed	10	knots	(MyShipTracking, n.d.-b)
One Way Cruising Duration	6.8	hours	3.4.5
Round trip cruising duration	13.6	hours	3.4.5
Cruising Engine Load	75	%	Assumed based on discussion with supervisor.
DP/Manoeuvring Engine Load (%)	25	%	Assumed based on discussion with supervisor.
DP/Manoeuvring Duration for round trip	4	hours	Assumed based on discussion with supervisor.
Main Engine Power per Unit	2010	kW	(Wärtsilä, n.d.-a, n.d.-b, 2024)
Number of Main Engines	4		(Wärtsilä, n.d.-a, n.d.-b, 2024)
Auxiliary Power Estimate	300	kW	Assumed based on discussion with supervisor.
Pilot Fuel Fraction	5	%	Assumed based on discussion with supervisor.
Ammonia LHV	18.6	MJ/kg	(Bicer & Dincer, 2018; Chalaris et al., 2022; Gilbert et

Category	Value	Unit	Reference
			al., 2018; Huang et al., 2022; B. A. Zincir & Arslanoglu, 2024)
LNG LHV	50	MJ/kg	(Bicer & Dincer, 2018; Chalaris et al., 2022; Gilbert et al., 2018; Huang et al., 2022; B. A. Zincir & Arslanoglu, 2024)
Pilot Fuel (MGO) LHV	42.7	MJ/kg	(Bicer & Dincer, 2018; Chalaris et al., 2022; Gilbert et al., 2018; Huang et al., 2022; B. A. Zincir & Arslanoglu, 2024)

3.2.4 Operational Profile Identification

The publicly available information regarding the operational profile of Viking Energy as a PSV was reviewed to determine the type of mission pattern for the vessel. The vessel functions on a shuttle type mission pattern in which the vessel operates from an onshore supply base and travels to various offshore Equinor installations on the Norwegian Continental Shelf before returning to the base. Such a function is common in PSV used in the transportation of fuel, water supplies, drilling fluids, and other materials required at the oil and gas drilling sites. Viking Energy has been deployed for this function as it was chartered to Equinor for a long-term period and thus making numerous trips to and from the base and the platform during its operational profile being suitable for defining a realistic round trip for this LCA case study (Eidesvik, n.d.-a, n.d.-b; MyShipTracking, n.d.-b; Norwegian Offshore Directorate, n.d.).

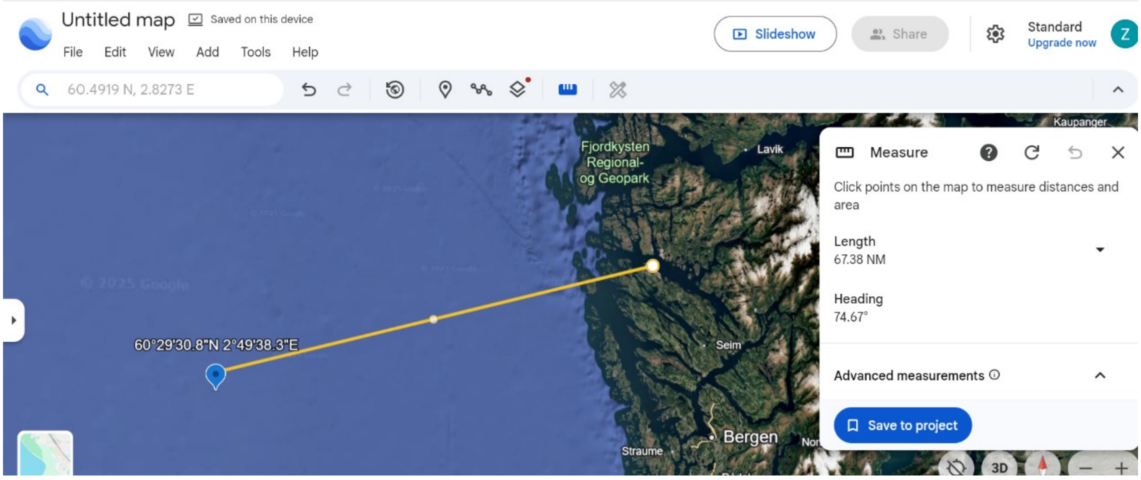
3.2.5 Identification of offshore destinations and coordinate collection

Since one of the destinations, Oseberg installation (Figure 15), is an offshore platform rather than a conventional port, platform coordinates were collected from an authoritative directory of Norwegian offshore facilities. This provided exact geographic latitude and longitude for candidate platforms, enabling transparency and reproducibility for sailing distance calculations (Norwegian Offshore Directorate, n.d.).

Figure 15. Oseberg Field Centre (Equinor, n.d.-b).

3.2.6 Distance measurement method selection and justification

The port-to-port and sea distance measurement online AIS tools, such as MyShipTracking (MyShipTracking, n.d.), MarineTraffic (MarineTraffic, n.d.), and VesselFinder (VesselFinder, n.d.), which are commonly used as navigation tools for route estimation, were used initially. However, these tools are effective for conventional ports only and were not helpful to locate the offshore installation. As a result, Google Earth version 10.96.0.1 multi-threaded (Google, n.d.) was used as a tool for measuring sailing distance between the onshore supply base and the offshore platform as shown in Figure 16, and also to identify the geographical coordinates of these two locations.



60.4919 N, 2.8273 E

Click points on the map to measure distances and area

Length
67.38 NM

Heading
74.67°

Figure 16. One-way sailing distance (NM) between Mongstad and Oseberg A installation.

3.2.7 Route definition and selection: Mongstad to Oseberg A and return

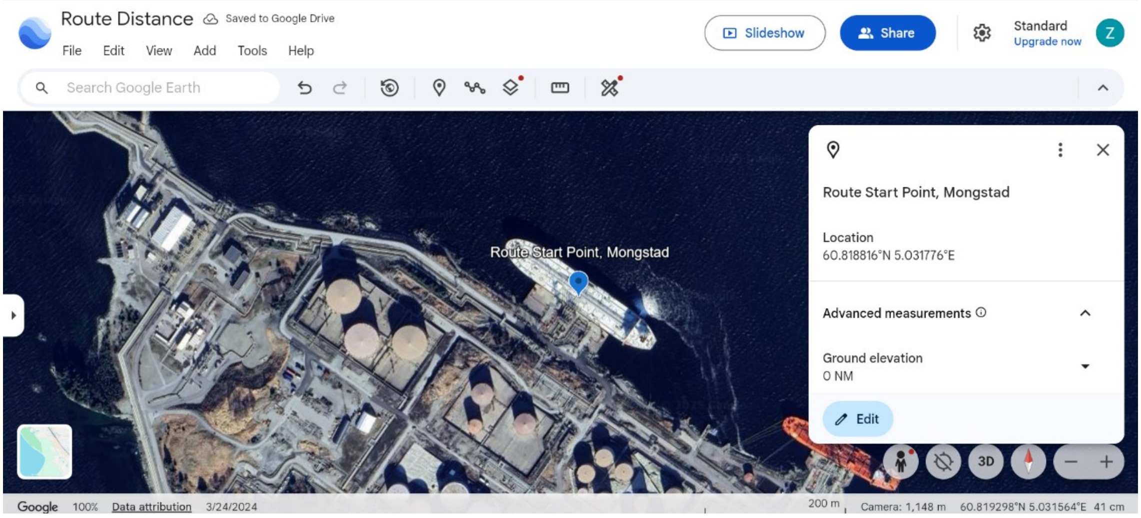
The initial and end point of the route is specified as the supply base of Mongstad (Equinor, n.d.-a), while the middle destination on the route is specified as the Oseberg A offshore oil platform (Equinor, n.d.-b; Norwegian Offshore Directorate, n.d.). The one-way distance was measured using Google Earth according to the geographical coordinates identified, while the round-trip distance was specified as twice the value of the one-way distance. Oseberg A was specified as the representative destination since it is an important oil and gas platform for Equinor that is frequently supplied from supply bases located across Norway. Geographical coordinates for the Mongstad supply base (Figure 17) and offshore Oseberg A platform (Figure 18) are locked as follows.

Mongstad supply base

- Latitude: 60.8167 N
- Longitude: 5.0333 E

Oseberg A platform

- Latitude: 60.4919 N
- Longitude: 2.8273 E



Route Start Point, Mongstad

Location
60.818816°N 5.031776°E

Ground elevation
0 NM

Figure 17. Geographical coordinates of the onshore supply base at Mongstad.

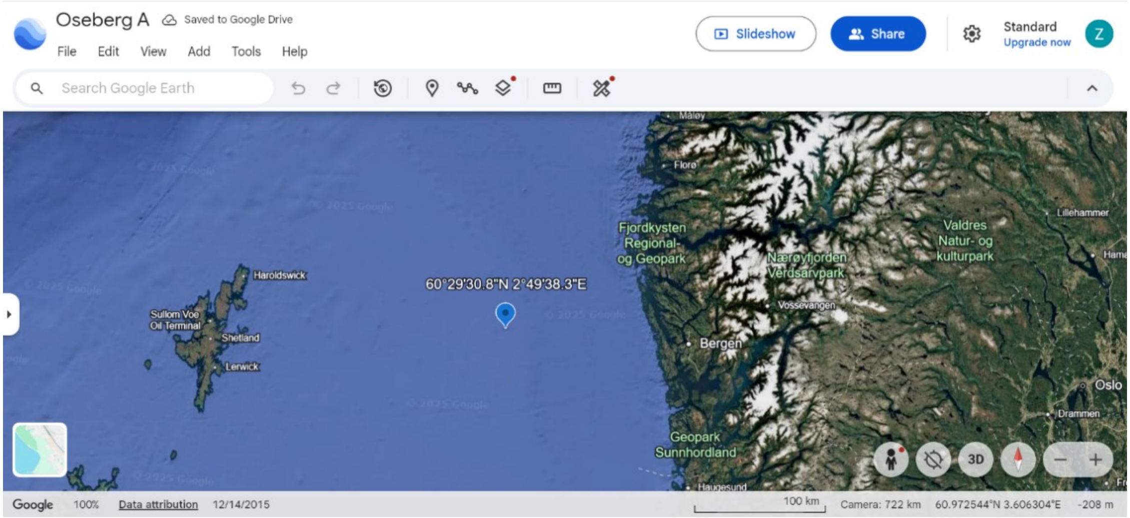


Figure 18. Geographical coordinates of the offshore installation at Oseberg.

3.2.8 Data integration into excel-based LCA calculator

All collected data was compiled into a structured LCA calculator built in Microsoft Excel specifically for this research. The calculator is organized into four main tabs, inputs, energy demand, fuel consumption and combustion emissions, each representing successive stages of the operational assessment. The input section houses all vessel specifications, operational assumptions, route data, and fuel properties. The energy demand tab is designated to utilize the input parameters and convert them to required propulsion and auxiliary energy demand per round trip. The third tab named fuel consumption is placed to convert the energy demand into fuel mass required of each fuel. The fourth tab, combustion emissions include the emissions and emission factors for each fuel. This is designed to calculate emissions for each fuel and configuration. It also has IPCC GWP factors for each pollutant and GWP is calculated for each pollutant, for each fuel and then for both configurations. It also applies break even N_2O reduction requirement for green ammonia to perform better than LNG, SCR treatment calculations, and then it has indicative NOx calculations for LNG and ammonia.

3.3 Measurement units and conventions

Sailing distances for the complete voyage are expressed in nautical miles (NM) and the unit for speed of the vessel is taken as knots, both consistent with the standard maritime practice. Power demand is measured in kilowatts, energy demand is measured in megajoules, and fuel consumption is reported in kilograms. Pollutant emissions are expressed in kilograms and climate impact is reported as kilograms of CO_2-equivalent using 100-year GWP factors. **Table 7** lists the parameters considered in this study along with their corresponding measurement units.

Table 7. Parameters and their respective measurement units.

Parameter	**Unit**
Sailing distance	Nautical miles (NM)
Vessel speed	Knots (kt)
Power demand	Kilowatts (kW)
Energy demand	Megajoules (MJ)
Fuel consumption	Kilograms (kg)
Pollutant emissions	Kilograms (kg)
Climate impact	kg CO_2-equivalent

3.4 Operational assumptions

3.4.1 Vessel average speed assumption

Even though the design service speed for Viking Energy is reported as 16 knots, publicly available AIS tracking data analysis shows that this vessel operates at considerably lower average speeds for the offshore supply mission. Indeed, observed average speeds from vessel tracking platforms are around 10 knots. Therefore, an average operational speed of 10 knots was selected for the LCA to better represent realistic operational conditions (MyShipTracking, n.d.-b).

3.4.2 Engine Load Assumption

The main engines are assumed to be operating at 75% load for the vessel's cruising duration throughout the complete voyage starting from the onshore supply base at Mongstad to the offshore Oseberg A installation and back to Mongstad. Whereas a reduced engine load of 25% is assumed for the maneuvering and DP modes around the platforms.

3.4.3 Pilot fuel fraction assumption

The pilot fuel fraction representing the proportion of the pilot fuel MGO required to initiate the combustion in both fuel configurations in this study is assumed to be 5%.

3.4.4 Auxiliary power demand assumption

Besides the power demand for ship propulsion, an assumption for average auxiliary electrical load was also applied to cover all onboard vessel operations, including lighting, hoteling, HVAC, and other auxiliaries. However, since there was a lack of publicly available auxiliary electrical power consumption data for the Viking Energy vessel, a constant auxiliary electrical power demand assumption was used with a value of 300 kW.

3.4.5 Cruising duration calculation

Vessel's cruising duration for one complete round trip is calculated based on the sailing distance between the supply base at Mongstad and the offshore Oseberg A platform and vessel's average operational speed. It can be calculated using the relation between distance and speed, such that the time spent on sailing equals the distance traveled divided by the average speed. Based on the already measured distance between Mongstad and the offshore installation, which is 68 NM and the documented average speed of 10 knots for the vessel, the cruising duration is calculated as 6.8 hours for one way trip as shown in equation (2). Thus, the total time taken for one complete round voyage by the vessel is 13.6 hours. This is illustrated below.

$$\text{Cruising Duration (hours)} = \text{Distance (NM)/Average speed (knots)} \tag{2}$$

$$\text{One way cruising duration } = \frac{68\ NM}{10\ knots} = 6.8\ hours$$

$$\text{Round trip cruising duration } = 6.8 \times 2 = 13.6\ hours$$

$$\text{Cruising duration per round trip } = \text{ 13.6 hours}$$

3.4.6 Dynamic positioning and maneuvering duration

Besides the vessel's cruising phase time, the time consumed during the maneuvering and DP operations is also incorporated into the operational profile of the vessel. As information related to the specific voyage for the case study vessel was not publicly available, the time spent on maneuvering and DP activities such as port approach, cargo handling, and departure is assumed to be 4 hours for each round voyage.

3.4.7 Emission control assumptions: SCR treatment of N_2O

The only major pollutant contributing to the GWP for the green ammonia combustion is N_2O. Therefore, exhaust after-treatment of N_2O emissions is crucial for the assessment of the environmental implications of using ammonia as a potential carbon free marine fuel.

SCR and other catalytic after-treatment technologies have been reported in the literature as effective measures to reduce N_2O emissions under ammonia-engine exhaust conditions. However, experimental studies performed within a wide range of operating conditions invariably show that N_2O conversion depends strongly on operating temperature, exhaust composition (NH_3, O_2, and H_2O), catalyst formulation, and catalyst aging. No single fixed SCR efficiency for N_2O reduction has, therefore, been defined (Cano Blanco et al., 2024).

Existing experimental evidence reveals that under unfavorable operating conditions where the exhaust water content, NH_3 slip, and exhaust temperatures are not within the desired ranges the levels of N_2O conversion may be restricted to low to moderate levels, approximately about 20 to 40%. However, under favorable operating conditions like higher operating temperatures around 450 to 500 °C and optimized catalyst formulations, N_2O conversion exceeding 90% and approaching near-complete removal has been reported (Guan et al., 2026; Zhuang et al., 2024).

With that in mind, this LCA has accounted for such variability with transparency and methodological soundness through a scenario-based approach. Following two scenarios were defined for the application of SCR systems on the N_2O exhaust treatment:

I. A conservative scenario, where the SCR system’s efficiency is assumed to be 20%, representing unfavorable yet reasonable operating conditions for the vessel operating offshore (for example, high water content, too much NH_3 slip, undesirable temperature distribution, and partial catalyst deactivation), and

II. An optimistic scenario, where the SCR system's efficiency is assumed to be 90%, representing a set of favorable operating conditions like optimal catalyst formulation and temperature.

The assumed SCR efficiency percentages applied in both these scenarios are thus based on experimentally reported conversion ranges under ammonia-engine-relevant SCR conditions, rather than relying on a single assumed efficiency.

3.5 Life cycle inventory

3.5.1 System boundary

The LCI is defined by selecting the TTW system boundary for this LCA study. TTW system boundary only includes the operational emissions. Upstream emissions related to fuel extraction, production, processing, storage and transportation are excluded from the scope of this study. The selected TTW system boundary is consistent with the IMO's defined boundary conditions and thus suitable for assessing operational emissions of alternative marine fuels under a realistic vessel operational profile.

3.5.2 Functional unit

The functional unit for this LCA is defined as one complete round trip of the vessel starting from the onshore supply base Mongstad to the offshore Oseberg A platform and back to the Mongstad supply base. The reference flow is established by connecting the operational energy demand required for one complete round trip to the corresponding fuel mass consumption for each fuel configuration and the subsequent amount of emissions produced for each configuration. All LCI flows, including energy demand, fuel consumption, and combustion emissions are linked to this functional unit.

3.5.3 Fuel properties

This study revolves around three fuels, green ammonia and LNG, being the main comparative alternative marine fuels are the two primary fuels of this study. The third, selected pilot fuel for both configurations is MGO. The LHVs of these fuels were selected based on a literature re(Bicer & Dincer, 2018; Chalaris et al., 2022; Gilbert et al., 2018; Huang et al., 2022; G. N. Lee et al., 2022; B. A. Zincir & Arslanoglu, 2024)B. A. Zincir & Arslanoglu, 2024) on alternative marine fuels. Across these studies, LHV for ammonia has consistently been reported as 18.6 MJ/kg. LHV for LNG ranges from 48 to 50 MJ/kg, a value 50 MJ/kg was selected for this study. Reported LHV values for MGO range between 41 and 43 MJ/kg with 42.7 MJ/kg adopted as a commonly reported value. These selections are consistent with values used in prior marine LCA studies.

3.5.4 Energy demand inventory

The energy demand inventory includes the propulsion energy required during cruising for 13.6 hours, propulsion energy required during DP and maneuvering for 4 hours and the onboard auxiliary energy requirement throughout the complete round trip of the vessel for 17.6 hours. This is the total operational energy requirement for the TTW system boundary of this study. 95% of this energy demand is supplied by the main fuel and only 5% of the demand is supplied via pilot fuel.

3.5.5 Fuel consumption inventory

Similarly, fuel consumption inventory includes the fuel mass required to fulfil the required operational energy demand per round trip. This includes the fuel mass (Kg) of all of the three fuels, ammonia, LNG, and MGO.

3.5.6 Emissions inventory

The emissions inventory includes the GHG exhaust emissions produced during the fuel combustion for the TTW system boundary. **Table 8** summarizes the fuels and their associated emissions. Green ammonia generates N_2O and ammonia slip as the main pollutants during its combustion. For LNG, CO_2, CH_4, and N_2O are the dominant climate emissions associated with its combustion. Pilot fuel, MGO used in both configurations, generates the similar emissions like LNG, such as CO_2, methane slip, and N_2O. Since, NO_x is only a regulated air pollutant and not treated as an active pollutant within the GWP, they are quantified and reported separately. All the emissions are quantified at the exhaust stage only; no upstream or nonoperational emission sources are considered in this study.

Table 8. Fuels and their main emissions for the TTW boundary.

Fuel Type	**System Boundary**	**Main Emissions / Pollutants**
Green ammonia	TTW	N_2O, NH_3 (ammonia slip)
LNG	TTW	CO_2, CH_4 (methane), N_2O
MGO (pilot fuel)	TTW	CO_2, CH_4 (methane slip), N_2O

3.6 Operational energy demand and fuel consumption calculations

To calculate the total energy demand per round trip, first energy required for cruising, DP, maneuvering and onboard auxiliary needs was calculated. To calculate the total fuel consumption per round trip for each configuration, first fuel consumption of each fuel was calculated individually including green ammonia, LNG and pilot fuel MGO.

3.7 Emissions and impact calculation method

To calculate the total emissions for both configurations, firstly the GHG pollutants for each fuel were identified and then their corresponding emission factors were collected from the peer reviewed articles focused on maritime fuels and emissions (see **Table 14**) (Ramsay et al., 2023). Similarly, to calculate GWP for both configurations, IPCC 100-year GWP factors for each pollutant were collected first (see **Table 17**) and then GWP of each pollutant for each fuel per round trip was calculated (see **Table 18)** with the help of following equation.

$$\mathrm{GWP}_i = E_i \times \mathrm{GWP}_i^{100} \tag{3}$$

Where:

- GWP_i= total global warming impact of pollutant *i* (in CO_2-equivalents)
- E_i= mass of emissions of pollutant *i* (e.g., kg)
- GWP_i^{100}= IPCC 100-year GWP factor for pollutant *i*

4 Results

Table 9 from the excel LCA calculator shows the total energy demand for one complete round trip of the vessel. Here, propulsion power required during cruising and DP were calculated assuming the 75% and 25% engine loads for the simultaneous phases. Similarly, energy demand was calculated for cruising, manoeuvring, and auxiliary needs based on the time duration of each. That provides us with the total energy required for one round trip.

Table 9. Total energy demand for one complete round trip.

Component	**Equation**	**Energy**
Propulsion Power Required During Cruising	P_cruise = P_engine × LF_cruise	8040 KW * 0.75 = 6030 KW
Propulsion Energy Required During Cruising	E_cruise = P_cruise × t_cruise	6030 KW * 13.6 h = 82,008 KWh
Propulsion Power Required During DP/Maneuvering	P_DP = P_engine × LF_DP	8040 KW * 0.25 = 2010 KW
Propulsion Energy Required During DP/Maneuvering	E_DP = P_DP × t_DP	2010 KW * 4h = 8040 KWh
Auxiliary Energy Demand	E_aux = P_aux × t_total	300 KW * 17.6 h = 5280 KWh
Total Energy Demand Per Round Trip (KWh)	E_total = E_cruise + E_DP + E_aux	82008 + 8040 + 5280 = 95238 KWh
Total Energy (MJ)	E_MJ = E_total × 3.6	95238 × 3.6 = 343180.8

Table 10 shows the individual energy demand of pilot and main fuel for the complete trip. Having known the LHV of green ammonia, LNG, and the pilot fuel (**Table 11**) firstly individual fuel mass consumption for each fuel was calculated (**Table 12**) and is illustrated in **Figure 19**. After that total fuel mass consumption for each of two configurations was calculated (**Table 13)** and is illustrated in **Figure 19**. The fuel mass consumption for green ammonia plus pilot fuel configuration is 17929 Kgs while for LNG plus pilot fuel configuration it is 6922 Kgs.

Table 10. Individual share of pilot and main fuel in the total energy demand per trip.

Fuel	Equation	Energy demand per trip (MJ)
Pilot fuel energy per round trip	E pilot = E total × pilot fraction	343,180.8 × 0.05 = 17,159.04
Main fuel energy per round trip	E main = E total × (1 − pilot fraction)	343,180.8 × 0.95 = 326,021.76

Table 11. Fuels and their LHVs.

Fuel	Value (MJ/kg)
Green ammonia	18.6
LNG	50
Pilot Fuel	42.7

Table 12. Individual fuel mass consumption per trip for MGO, LNG and ammonia.

Fuel	Equation	Fuel mass consumption (Kg)
Pilot fuel	m pilot = E pilot ÷ LHV pilot	17,159.04 ÷ 42.7 ≈ 402
Green ammonia	m NH_3 = E main ÷ LHV ammonia	326,021.76 ÷ 18.6 ≈ 17528.05
LNG	m LNG = E main ÷ LHV LNG	326,021.76 ÷ 50 ≈ 6520.43

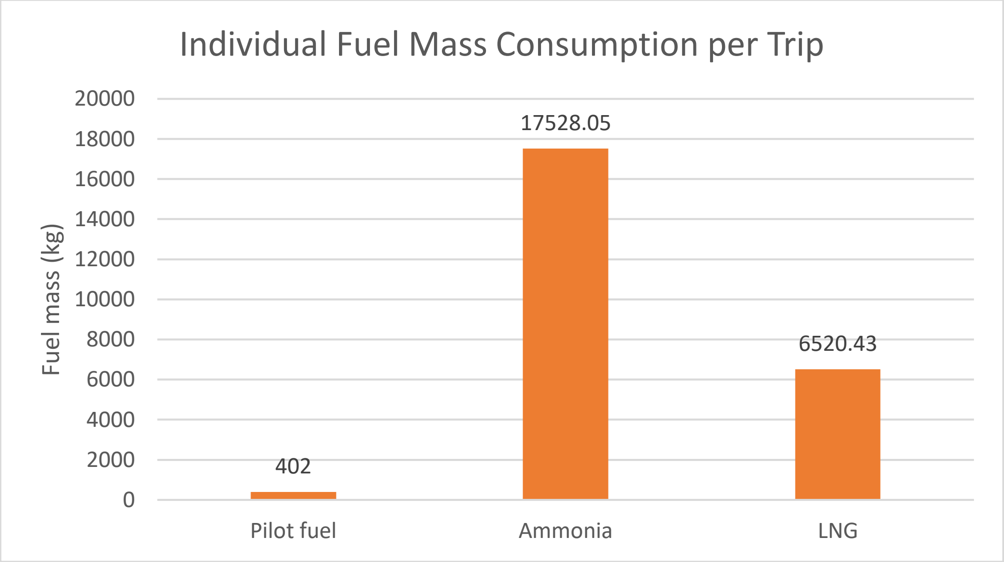


Figure 19. Individual fuel mass consumption per trip for pilot fuel, green ammonia, and LNG.

Table 13. Configuration level fuel mass consumption.

Fuel Configuration	Main fuel (kg)	Pilot fuel (kg)	Total fuel mass (kg)
Green Ammonia + Pilot Fuel	17527	402	17929
LNG + Pilot Fuel	6520	402	6922

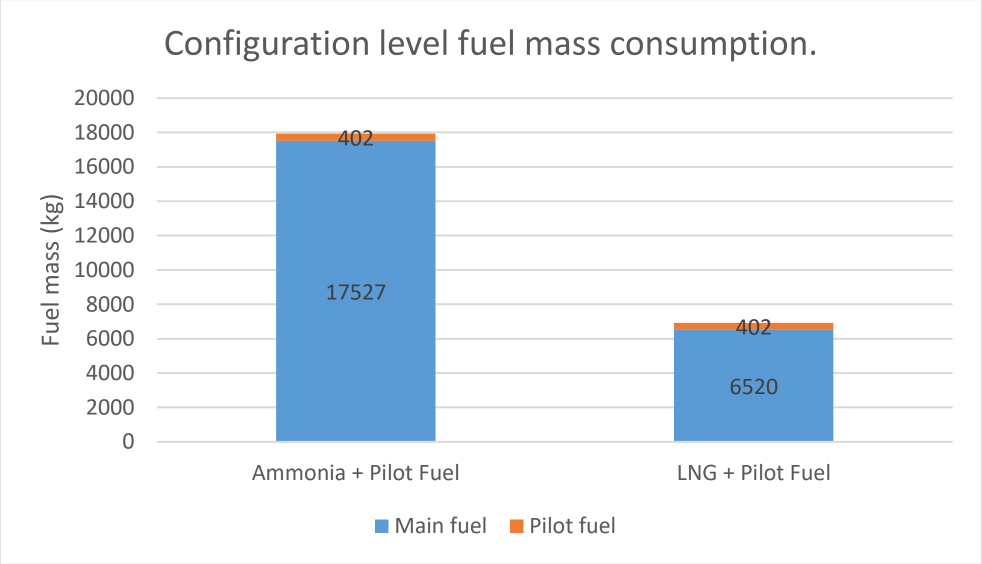


Figure 20. Total fuel mass consumption per trip for ammonia and LNG configurations, showing the contributions of main fuel and pilot fuel.

The pollutants and their respective emission factor values for each of the three fuels of the study are shown in **Table 14**.

Table 14. Pollutants and their emission factors (Ramsay et al., 2023).

Fuel	Emissions	Emission Factor (g/MJ)
LNG	CO_2	57.3
	CH_4	0.41
	N_2O	2.92×10^{-3}
Green Ammonia	N_2O	0.27
	NH_3	1.39
Pilot Fuel MGO	CO_2	75.1
	CH_4	1.41×10^{-3}
	N_2O	4.22×10^{-3}

Table 15 presents the calculated individual emissions of each pollutant and the total emissions for each of the three fuels of this study. The corresponding CO_2 emissions are illustrated in **Figure 21**, while the non-CO_2 emissions (CH_4, N_2O, and NH_3) are presented in **Figure 22**. Which then provides the configuration level emissions (**Table 16).**

Whereas, for each pollutant:

$$\text{Emission} = \text{Energy used (MJ)} * \text{Emission factor(g/MJ)} \tag{4}$$

Table 15. Individual pollutant emissions and total emissions for the three fuels.

Fuel	**Energy used (MJ)**	**CO_2 emissions (kg)**	**CH_4 emissions (kg)**	**N_2O emissions (kg)**	**NH_3 emissions (kg)**	**Total emissions (kg)**
Green Ammonia	326,021.7	-	-	88.02	453.1	541.1
LNG	326,021.7	18681.0	133.6	0.95	-	18815.6
Pilot MGO	17165.4	1289.1	0.02	0.07	-	1289.2

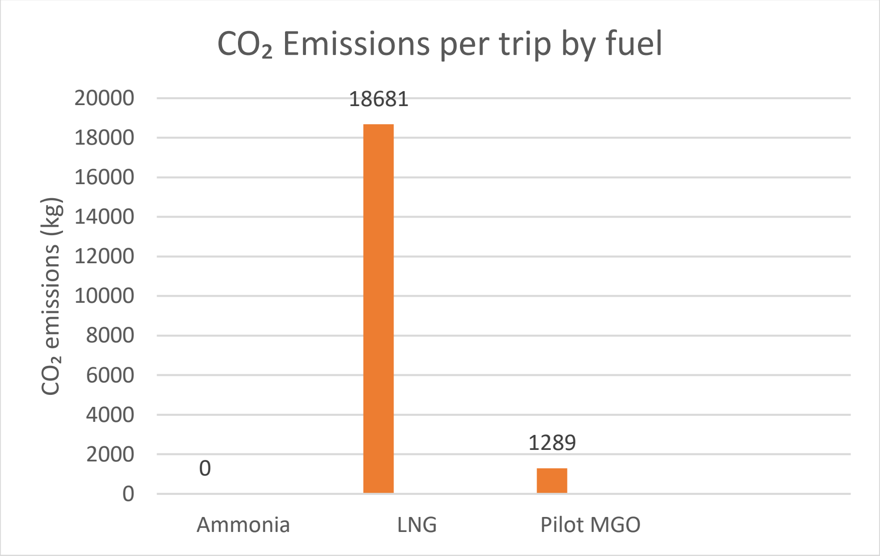


Figure 21. Comparison of CO_2 emissions per trip for ammonia, LNG, and pilot MGO fuels.

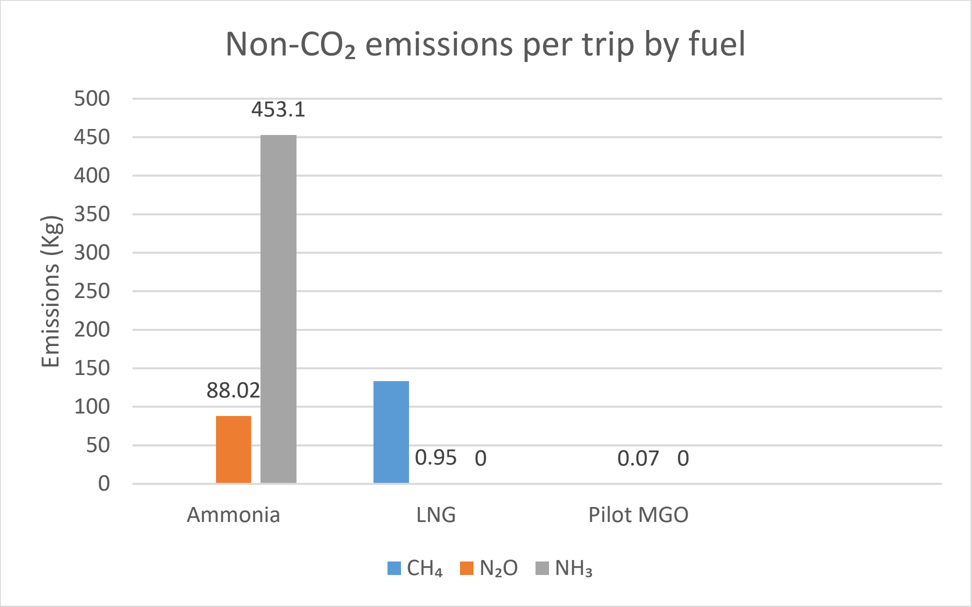


Figure 22. Comparison of CH_4, N_2O, and NH_3 emissions per trip for ammonia, LNG, and pilot MGO fuels.

Table 16. Configuration-level emissions.

Fuel Configuration	**Total Emissions (kg)**
Green Ammonia + Pilot Fuel	1830.4
LNG + Pilot Fuel	20104.8

Having known the IPCC 100-year GWP factors for each pollutant (**Table 17**), GWP for each pollutant was calculated as visible in **Table 18**Error! Reference source not found.**,** which ultimately provides the configuration level GWP (**Table 19**). This result clearly shows that the GWP of the green ammonia configuration is higher than that of the LNG. That is mainly because of the N_2O being the major pollutant of the green ammonia combustion with a very high GWP of 273.

Table 17. IPCC 100-year GWP factors.

Pollutant	**GWP_{100}**
CO_2	1
CH_4	27.2
N_2O	273
NH_3	0

Table 18. Individual GWP of each pollutant and total GWP of the three fuels.

Fuel	**Pollutant**	**GWP (Kg CO_2e)**	**Total GWP (Kg CO_2e)**
Green Ammonia	N_2O	24031	24031
LNG	CO_2	18681	22576.7
	N_2O	259.8	
	CH_4	3635.7	
MGO	CO_2	1289.1	1309.5
	N_2O	19.7	
	CH_4	0.65	

Table 19. Configuration level GWP.

Fuel Configuration	**GWP (Kg CO_2e)**
Green Ammonia + Pilot Fuel	25340.6
LNG + Pilot Fuel	23886.2

A break-even analysis, as shown in **Table 20** was conducted to determine the amount of reduction in N_2O emissions which is enough for green ammonia configuration to be at the same level as LNG configuration in terms of GWP. Based on the LCA results without any emissions control, the total GWP of green ammonia configuration is calculated as 25,340 KgCO_2e, whereas 23,886 KgCO_2e for LNG. The GWP difference between both is 1454.33 KgCO_2e, meaning only approximately 6.1% of fractional reduction in N_2O emissions from green ammonia combustion is enough to put the GWP of the green ammonia configuration at the same level as that of LNG configuration.

Based on the SCR scenarios discussed in section 3.4.7, two post SCR scenarios were evaluated as shown in **Table 21**. Both the conservative (20% N_2O emissions reduction) and optimistic (90% N_2O emissions reduction) scenarios show that the GWP of green ammonia decreases significantly if after treatment technologies are deployed as presented in **Figure 23**.

Table 20. Break-even analysis.

Break-even N_2O Reduction	
Difference Need to be Eliminated	ΔGWP = 25340.6194 - 23886.2884 = 1454.3 (Kg CO_2e)
Required Fractional Reduction in N_2O	1454.331/24031.0639 = 0.0605 ~6.1%

Table 21. Post SCR GWP of green ammonia.

Scenario Case	Assumed N_2O reduction	Recalculated GWP of green ammonia (Kg CO_2e)	Green ammonia + Pilot fuel GWP (Kg CO_2e)	GWP comparison vs LNG + Pilot fuel (Kg CO_2e)
No SCR	0%	24031	25340.6	Higher
Conservative	20%	19224.8	20534.4	Lower
Optimistic	90%	2403.1	3712.6	Much Lower

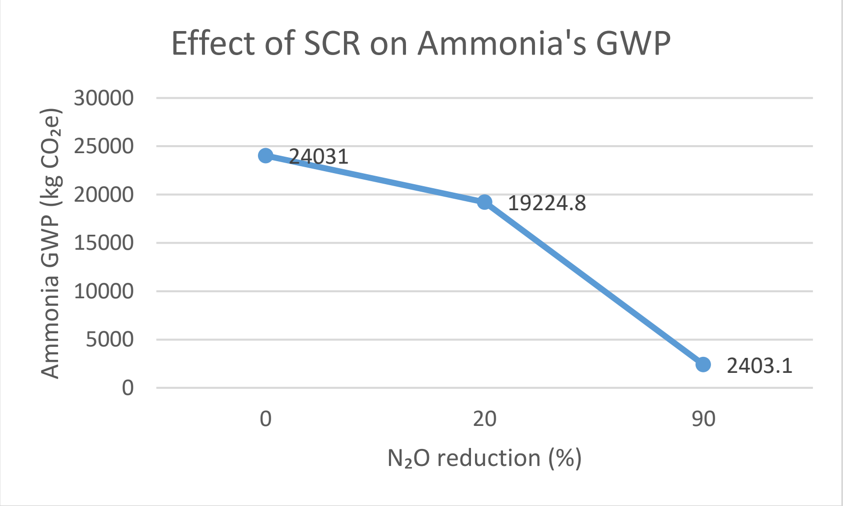


Figure 23. Effect of SCR on ammonia GWP at different efficiency levels.

Table 22 shows the emission factors for ammonia slip, and NOx, and **Table 23** shows the calculated NH_3 and NOx emissions. The indicative comparison for NOx emissions between the green ammonia and LNG configuration clearly shows that green ammonia produces approximately 1222 Kg more NOx emissions as compared to the LNG per round trip.

Table 22. GWP neutral pollutant emissions and their emission factors (Ramsay et al., 2023).

Fuel	Emissions	Emission Factors (g/MJ)
Green Ammonia	NH_3	1.39
	NOx	3.91
LNG	NOx	0.16
MGO	NOx	2.04
	NH_3	0.0003

Table 23. Ammonia slip and NOx emissions of each fuel.

Fuel	Energy Used (MJ)	NH_3 emissions (kg)	NOx emissions (kg)	Total Emissions (kg)
Green Ammonia	326,021.7	453.1	1274.7	1727.9
LNG	326,021.7	-	52.1	52.1
Pilot MGO	17165.4	0.005	35	35.005

5 Discussion

The results of this study provide insights into the comparative environmental performance of green ammonia and LNG as alternative shipping fuels in terms of their GWP under a TTW LCA framework. The analysis shows that without any control measure for the emissions, the N_2O emissions dominate the GWP for the green ammonia configuration, leading to a higher GWP compared to the LNG configuration. Even though green ammonia is a carbon free molecule, it can still cause higher GHG emissions as N_2O has a 100-year GWP value of approximately 273, which is significantly higher than that of CO_2 (US EPA, n.d.). Which means that over a 100-year period, one kilogram of N_2O traps about 273 times more heat in the atmosphere than one kilogram of CO_2.

This finding highlights a critical issue associated with the adoption of ammonia as a fuel. While ammonia emits no CO_2, even relatively small formation of N_2O emissions contributes disproportionately to the overall GHG emissions and can offset its climate advantage if not properly controlled. This finding is consistent with previous studies on ammonia combustion in marine engines, which identify N_2O as a critical emission due to its high GWP. For instance, studies by (Cheng et al., 2025; Pachiannan et al., 2025) report that N_2O is formed as an intermediate byproduct during ammonia oxidation and can dominate the overall greenhouse gas impact despite the absence of CO_2 emissions. Similarly, (Chavando et al., 2024) highlight that ammonia slip and incomplete combustion can further contribute to secondary N_2O formation, reinforcing the need for effective emission control strategies.

The dominance of N_2O emissions observed in this study is therefore in line with trends reported in the literature. While the overall behavior is consistent, variations in the magnitude of reported impacts across studies can be attributed to differences in system boundaries, emission factors, and the inclusion of emission control technologies. In particular, studies incorporating advanced after-treatment systems or optimized combustion strategies tend to report lower relative contributions of N_2O to total GWP.

It is also important to note that the use of pilot fuel contributes to emissions in both ammonia and LNG configurations. Since pilot fuels such as diesel or hydrogen are required to ensure stable combustion in ammonia engines, their contribution to emissions may partially offset the environmental benefits of ammonia. This also explains why certain emissions remain comparable across both fuel configurations in this study. However, future developments may reduce this dependency, for example through improved combustion strategies or by replacing conventional pilot fuels with renewable alternatives such as bio-based or synthetic diesel. Such approaches could further enhance the environmental performance of ammonia as a marine fuel.

The break-even analysis conducted in this study provides an important insight into the sensitivity of ammonia's environmental performance. It shows that a 6.1% reduction in the N_2O emissions leads to the GWP performance for the green ammonia being comparable to that of LNG. This threshold value lies way below the conservative reduction rates of N_2O emissions reported in the literature using SCR technologies for ammonia-based engines (Guan et al., 2026; Zhuang et al., 2024). As presented in the results section (see Table 20 & Table 21) that even the conservative scenario of SCR with 20% efficiency already shows a clear GWP advantage for green ammonia configuration over the LNG configuration. The optimistic scenario for SCR with 90% efficiency represents favorable operating conditions and results in a very low GWP value. This result shows the potential of green ammonia as a climate friendly marine fuel when effective N_2O abatement after treatments are integrated. This finding highlights the importance of integrating exhaust treatment systems for ammonia fueled marine engines to benefit effectively from its carbon neutral potential.

Alongside N_2O, green ammonia also produces more NOx emissions as compared to LNG. This outcome is expected, considering that the ammonia's combustion process involves N_2 based compounds that can result in NOx formation during high-temperature combustion reactions. High NOx emissions are a major environmental concern because NOx causes severe pollution and has implications for human health and marine ecosystems.

Therefore, NOx reduction strategies are critical if ammonia is to be adopted as a marine fuel.

The findings of the study contribute to the existing literature on the development of alternative marine fuels for the decarbonization of the maritime sector. LNG is considered as a transitional fuel because of its lower carbon emissions as compared to the conventional fossil fuels. However, it still produces CO_2 emissions and cannot achieve the complete maritime decarbonization goals. On the other hand, results of this study demonstrate that green ammonia indeed possesses a climate benefit over LNG because of its carbon free nature provided that advanced emission technologies are integrated with ammonia fueled engines.

There are still a number of challenges and hurdles that need to be overcome for the practical application of ammonia. These include combustion stability, toxicity, storage, safety, and emission control issues. The findings of the research highlight the fact that the benefits of ammonia to the environment are heavily dependent on the technological advancements that are being made to avoid the production of N_2O and NOx during the combustion process. Therefore, the future of ammonia engine technology, combustion stability, after treatment strategies, and safety is crucial for the successful application of ammonia as a marine fuel.

It is also important to understand that the results of the study need to be considered within the scope of the study’s methodological boundaries and assumptions. The study was performed based on a TTW LCA framework, where the study focused on emissions that are produced during the combustion of the fuels only. Therefore, it did not consider the emissions that are produced during the production, processing, and transportation of fuels. A WTW LCA might give a better and broader scope of the results for the study, especially when considering the sources of energy that are used to produce ammonia. Future research can extend this work by integrating the WTT phase and evaluating the complete life cycle environmental performance of ammonia compared to other emerging alternative marine fuel options. In addition, the calculations performed in this study provide a transparent and structured analysis of emissions, demonstrating that a spreadsheet-based approach using Microsoft Excel can be effectively applied for TTW LCA. The results indicate that, when supported by clearly defined assumptions and reliable input data, Excel can be used in a comparable manner to dedicated LCA tools such as SimaPro for this type of assessment.

Overall, this study highlights both the opportunities and the challenges associated with using green ammonia as a shipping fuel. While ammonia enables carbon-free combustion, its environmental performance is highly dependent on effectively managing nitrogen-related emissions. If supported by advanced emission control technologies and continued technical development, ammonia could become a practical and competitive option for long-term maritime decarbonization.

6 Conclusion

The study assessed the greenhouse gas performance of green ammonia and LNG as alternative marine fuels through a TTW LCA method on a representative offshore supply vessel on a specified round trip route from Mongstad to Oseberg A. The study assessed the operational emissions and the GWP of two fuel configurations, green ammonia and LNG both with MGO as pilot fuel.

The results show that the relative climate performance of these fuels is significantly impacted by fuel specific emissions. For LNG fuel, CO_2, and CH_4 emissions are generated during combustion. For ammonia fuel, the emissions are dominated by N_2 based emissions such as N_2O and ammonia slip during combustion. Due to the high GWP of N_2O emissions, these emissions can impact on the overall greenhouse emissions from ammonia-fueled engines. In addition, using MGO as a pilot fuel contributes to CO_2, CH_4, and N_2O emissions in both configurations, further influencing the overall emission profile.

The results reveal that the environmental advantage of green ammonia is largely contingent on the management of N_2O emissions. Scenario analysis revealed that green ammonia can significantly lower the environmental impact of ammonia-fueled propulsion systems through the implementation of N_2O emissions mitigating technology such as SCR. Consequently, ammonia has the potential of reducing GHG emissions compared to LNG during the operational phase after the effective reduction of N_2 based emissions.

This research contributes to the existing limited research on maritime LCA by offering a clear and reproducible TTW assessment approach that is underpinned by explicit operational assumptions and voyage-based energy demand modeling. By applying this assessment approach to a specific vessel configuration and well-specified operational conditions, this research offers a more transparent approach to modeling emissions and a better understanding of the operational climate impacts of different marine fuels. In addition, the use of Microsoft Excel proved to be a suitable and transparent tool for conducting the TTW LCA, enabling clear traceability of input data, flexibility in calculations, and reproducibility of results without reliance on specialized LCA software. This demonstrates that robust LCA assessments can be performed using accessible tools when supported by well-defined assumptions and structured modeling.

However, these results should be appreciated in the context of the scope of the analysis. It should be noted that the analysis only considered emissions for the TTW stage and therefore does not include emissions associated with fuel production and supply. Furthermore, the results are based on a single vessel type, route, and set of assumed parameters. Furthermore, the accuracy of LCA results largely depends on the quality and representativeness of the input data. In this study, several emission factors and performance parameters were derived from literature sources and assumptions due to the limited availability of experimental data for ammonia-fueled marine engines. The technical and operational specifications of the case vessel were also obtained from publicly available sources, which may not fully capture real-world operational variability. This introduces a degree of uncertainty in the results, highlighting the need for more empirical and high-resolution data to improve the robustness of future assessments.

Future research must extend the system boundary to WTW, consider other vessel types and operating profiles, and continue to explore the impact of emission control technologies and engine types on the environmental performance of ammonia-fueled vessels. Data on experimental measurements for emissions and after-treatment performance during ammonia combustion will be vital in increasing the accuracy of future LCA research.

Overall, the results demonstrate that while LNG has some potential as a bridging fuel with associated emissions reductions relative to conventional maritime fuels, green ammonia has considerable scope to contribute to future maritime decarbonization if N_2 emissions can be managed.

7 Summary

Maritime shipping is an essential factor in global trade, and it facilitates the transport of most international goods. It has been recognized that maritime shipping sector contributes significantly to GHG emissions, making it a substantial anthropogenic source. There has been an increase in regulatory pressure from international and regional regulations, including the IMO's GHG reduction strategy and EU climate regulations. This has made it necessary to look into decarbonization in maritime transport. The shift from conventional fuels to low and no carbon fuels has become an important aspect. Among all the fuels that are under consideration in maritime transport, including those that could be used in decarbonization, LNG has been considered an important fuel due to low-carbon emissions, and ammonia has become an important fuel for the future because of its carbon-free nature.

Despite the rising interest in these fuels, their environmental performance in maritime applications remains unclear. Existing studies have shown mixed results due to differences in LCA methodology, boundaries, emission factors, and operation-related assumptions. Besides, ammonia fuels have shown a lack of representation in maritime LCA studies, especially those related to green ammonia fuels. To bridge these research gaps, the GHG performance of green ammonia and LNG fuels in maritime applications was assessed in the research through a transparent LCA methodology.

The research aimed at developing a voyage-based operational model for a PSV called Viking Energy on a specified route connecting a supply base at Mongstad with an offshore installation at Oseberg A. The functional unit of the research was determined as a complete round trip between these two locations. Based on the power demand of the vessel during cruising, DP, and auxiliary operations, the operational energy demand of the vessel was estimated. Using the calculated energy demand of the vessel, fuel consumption was determined using green ammonia with pilot MGO and LNG with pilot MGO as fuels. Using the calculated fuel consumption of the vessel with different fuels, GHG emissions were estimated using emission factors. The overall impact of the fuels on the environment was determined using the factors of GHG based on the 100-year GWP of the Intergovernmental Panel on Climate Change.

The findings indicate a clear difference in the GHG emission profiles of the two fuels, primarily driven by their combustion characteristics. While the use of LNG emits CO_2 and CH_4, the use of ammonia mainly emits N_2 based GHGs, such as N_2O and ammonia slip. Given the exceptionally high global warming potential of N_2O, even relatively small emission levels can substantially influence the overall GHG impact of the system. The analysis therefore shows that the environmental performance of ammonia is strongly governed by the extent to which nitrogen-based emissions are controlled.

In summary, the study demonstrates that LNG can lower GHG emissions during vessel operations when compared with conventional marine fuels, supporting its role as an interim solution in the shipping sector. At the same time, green ammonia offers the possibility of achieving much deeper emission reductions during operation, provided that nitrogen-related emissions are effectively managed. The study also contributes to the existing body of knowledge by presenting a clear and transparent TTW assessment framework, built on well-defined and explicitly stated operational parameters.

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