



Life cycle analysis of ammonia fuelled ship – case ship studies for marine vessels

Haibin Wang^{a,*}, Peilin Zhou^a, Byongug Jeong^a, Ana Mesbahi^a, M.P. Mujeeb-Ahmed^a, Hayoung Jang^a, Alexandros Giannakis^b, Konstantinos Sykaras^b, Astrinos Papadakis^b

^a Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Henry Dyer Building, 100 Montrose Street, Glasgow, G4 0LZ, UK

^b Hydrus Engineering S.A., 515 Mesogeion Ave., 153 43, Agia Paraskevi, Greece

ARTICLE INFO

Keywords:

Shipping
Decarbonisation
Life cycle analysis (LCA)
Ammonia fuel
Alternative fuels

ABSTRACT

In response to the International Maritime Organization's (IMO) strategy to achieve net zero greenhouse gas emissions from international shipping by around 2050, alternative fuels present a viable option and it is critical to assess the environmental performance of alternative marine fuels. Since ammonia stands out as a strong contender due to its zero-carbon content, this paper employs a life cycle analysis (LCA) methodology to assess the environmental impacts of ammonia as a marine fuel, assessing its contributing potential on global warming, acidification, eutrophication, and photochemical ozone creation. A case study of a multi-purpose dry-cargo heavy lift vessel is analysed, focusing on two key aspects: ammonia fuel and fuel containment tanks, covering production, transport, storage, bunkering, usage, and recycling. The findings highlight the advantages of various ammonia fuels from different production processes in minimizing environmental impacts across its life cycle compared to traditional fossil fuels. The results indicate that unlike blue and green ammonia, the brown ammonia—produced from fossil fuels without carbon emission reduction techniques—results in higher life cycle emission release than the traditional marine fuels. Additionally, the study extends the LCA to various ship types to showcase ammonia's benefits as a marine fuel and the potential that is associated with. Recommendations are provided for the marine industry on integrating LCA into alternative fuel evaluations, promoting a comprehensive understanding of their environmental impacts.

Acronym

A/E	Auxiliary Engine
AI	Acidification Impact
AP	Acidification Potential
C ₂ H ₄	Ethylene
CCS	Carbon Capture and Storage
CML	Centre of Environmental Science of Leiden University
CO ₂	Carbon Dioxide
CSR	Service Continuous Rating
EI	Eutrophication Impact
EP	Eutrophication Potential
EU	European Union
GF	Glass Fibre
GWI	Global Warming Impact
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
KPI	Key Performance Indicators

(continued on next column)

(continued)

LCA	Life Cycle Analysis
LCIA	Life Cycle Impact Assessment
LNG	Liquefied Natural Gas
M/E	Main Engine
MDO	Marine Diesel Oil
NH ₃	Ammonia
NOx	Nitrogen Oxides
PM	Particle matters
PO ₄ ³⁻	Phosphate
POCI	Photochemical Ozone Creation Impact
POCP	Photochemical Ozone Creation Potential
SFOC	Specific Fuel Oil Consumption
SO ₂	Sulphur dioxide
SOx	Sulphur Oxides
TtW	Tank to Wake
VOC	Volatile Organic Compounds
WtT	Well to Tank
WtW	Well to Wake

* Corresponding author.

E-mail address: haibin.wang@strath.ac.uk (H. Wang).

<https://doi.org/10.1016/j.jclepro.2025.146105>

Received 31 March 2025; Received in revised form 19 June 2025; Accepted 30 June 2025

Available online 3 July 2025

0959-6526/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The global marine industry faces growing pressure to minimize its environmental impact, particularly due to stringent international regulations designed to limit greenhouse gas (GHG) emissions, air pollution, and the use of detrimental marine fuels. Traditionally, marine vessels have high dependency on heavy fuel oil (HFO), which poses significant environmental risks, including elevated sulphur and nitrogen oxide emissions, particulate matter, and GHGs. In 2023, the International Maritime Organization (IMO) updated its ambitious goals to cut total annual GHG emissions by 20 % by 2030, 70 % by 2040, and achieve net-zero by or around 2050, relative to 2008 levels. This revision intensifies the urgent need for sustainable and eco-friendly alternative fuels. One promising alternative is ammonia (NH₃), which could serve as a zero-carbon solution when derived from renewable sources.

Ammonia, proposed as marine fuel, boasts the benefit of emitting no CO₂ during combustion. Nonetheless, like any fuel, its environmental effect goes beyond just the usage phase. To grasp its overall environmental consequences, it's important to examine ammonia's entire life cycle, from production to disposal. This is where Life Cycle Assessment (LCA) becomes essential. LCA offers a thorough framework for evaluating the environmental impacts associated with a product or process from its inception to its end-of-life, addressing various stages such as raw material extraction, production, transportation, utilization, and final disposal.

The use of LCA in the marine sector has been developed in response to the industry's increasing need to evaluate and reduce environmental impacts. As the transition to cleaner fuels and technologies accelerates, LCA has become essential for assessing the actual environmental benefits of alternative fuels such as liquefied natural gas (LNG), hydrogen, and ammonia. It also facilitates comparisons between conventional fossil fuels and emerging options, offering shipowners, regulators, and policymakers valuable data-driven insights for informed decision-making.

A comprehensive LCA will be carried out to evaluate the environmental impacts of ammonia-fuelled vessels throughout their entire life cycle. This assessment will encompass both one demonstrator ship and five desktop studies, comparing conventional and composite storage tank solutions while considering their environmental implications. The LCA will take a holistic approach, examining key environmental factors such as carbon dioxide, sulphur oxides, nitrogen oxides, particulate matter emissions (CO₂, SO_x, NO_x, and PM). The study will assess emissions and environmental impacts across all life cycle stages of ships and storage tank structures, from cradle to grave. It will incorporate data from the NH3CRAFT project (NH3CRAFT, 2022), along with information gathered from databases and literature. Using LCA methodologies such as CML and ReCiPe, the study will quantify pollutant impacts within selected environmental impact categories, including Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP) and Photochemical Ozone Creation Potential (POCP). Eventually, the impacts will be determined as GWI, AI, EI and POCl. Furthermore, a sensitivity analysis will be conducted to evaluate the influence of parameter variations on LCA results, while an uncertainty analysis will be performed to determine the confidence levels of the collected data.

This study will also examine ammonia production, considering both green and conventional methods, along with its storage, transportation, and combustion phases, with a particular focus on NO_x emissions. By assessing each stage of the life cycle, the study aims to quantify the overall environmental performance of ammonia as a marine fuel, identify potential trade-offs, and highlight opportunities for improvement. Applying LCA to ammonia fuel and its storage tanks will provide

stakeholders with valuable insights into the sustainability of this alternative fuel. The findings will support decision-making for policymakers, researchers, and industry leaders, helping to drive the development of more environmentally friendly technologies and practices in the energy sector. As the transition to sustainable energy solutions advances, LCA will remain essential for understanding and minimizing the environmental impacts of ammonia fuel throughout its life cycle. The results of this study will contribute to the development of an exploitation plan for ammonia as a marine fuel and facilitate a detailed evaluation, ultimately offering critical insights to support its adoption as a sustainable alternative in the maritime sector.

2. Literature review

2.1. Alternative marine fuels

The shipping industry is actively exploring alternative fuels to meet decarbonisation goals set by the IMO and other global climate agreements. Alternative fuels such as hydrogen, ammonia, Liquefied Natural Gas (LNG), and biofuels have emerged as potential solutions for reducing GHG emissions in shipping (Al-Enazi et al., 2021; Harahap et al., 2023; Inal et al., 2022). Each fuel comes with unique environmental, technical, and economic trade-offs.

LNG has gained widespread adoption as a transition fuel, offering significant reductions in sulphur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter emissions. However, methane slip which is the unburned release of methane during combustion, limits its climate benefit and raises concerns about its long-term sustainability (Al-Enazi et al., 2021; Ampah et al., 2021). While LNG infrastructure is growing, its fossil origin and partial decarbonisation potential suggest it may serve only as a medium-term solution (Tomos et al., 2024).

Methanol is considered a viable alternative due to its ease of handling, compatibility with current infrastructure, and lower local pollutant emissions. However, its low energy density requires larger storage volumes, and unless produced from renewable sources, such as biomass or electrolysis (bio- or e-methanol), its lifecycle GHG reduction is limited (Islam Rony et al., 2023; Perčić et al., 2020). Methanol's appeal lies in its lower retrofit costs and ability to meet short-term regulatory compliance, although its use in deep-sea shipping remains constrained.

Hydrogen is widely regarded as a zero-emission fuel, especially when used in fuel cells. It produces only water vapour when combusted, offering complete decarbonisation potential. However, its use is restricted by storage complexity (requiring cryogenic temperatures of $-253\text{ }^{\circ}\text{C}$), high production costs, and limited bunkering infrastructure (Inal et al., 2022; Karvounis et al., 2024). Traditional grey and blue hydrogen production methods are slowly turning to green hydrogen, derived via electrolysis using renewable electricity, which is preferred for environmental performance (Wang et al., 2024).

Biofuels, including biodiesel, Fischer-Tropsch Diesel, and bio-methanol, are attractive for their ability to be used in existing engines with minimal modification. When sourced from waste biomass or advanced feedstocks, they can reduce lifecycle GHG emissions by up to 80 % (Kourkoumpas et al., 2024). However, life cycle assessments must account for indirect emissions to fully understand their sustainability and economic performance (Kourkoumpas et al., 2024; Mandegari et al., 2023).

Battery-electric propulsion system has been considered in many different types of ship and transportation: offshore support vessel, short sea high speed ferry, harbour tugboat, autonomous ships, fishing vessel and ocean going vessel, accounting on the characteristics of zero operating emission and excellent energy efficiency (Zobaa et al., 2023). However, it also emphasizes that with current technology, battery installation on ocean going vessel is technically feasible and can meet the decarbonisation requirement set by the IMO but economically impractical due to weight, cargo issues as well as the long voyages and

the high energy requirements (Arabnejad et al., 2024; Zobaa et al., 2023).

Ammonia is increasingly viewed as one of the most promising carbon-free marine fuels. It contains no carbon atoms and thus emits no CO₂ during combustion (Bicer and Dincer, 2018; Machaj et al., 2022). Ammonia can be used in both internal combustion engines and solid oxide fuel cells (SOFCs), offering flexible propulsion options. However, combustion produces NO_x and potentially N₂O, both of which are potent GHGs requiring advanced mitigation strategies such as selective catalytic reduction (Liu et al., 2024; Lu et al., 2024; Wei et al., 2024).

From an operational standpoint, ammonia's toxicity and corrosiveness require careful handling, leak detection systems, and crew safety protocols (Ejder and Arslanoğlu, 2022). Although green ammonia (produced via renewable electricity) is ideal, it remains expensive. Blue ammonia, made with natural gas and carbon capture, may serve as a transitional option (Wu et al., 2023; Zincir, 2022). Studies also suggest that ammonia-powered ships may be more economically viable as new builds rather than retrofits (Ejder and Arslanoğlu, 2022; Wu et al., 2022).

2.2. LCA of alternative marine fuels

LCA is a widely used tool to evaluate the environmental impacts of alternative fuels across their entire lifecycle—from production through to use on board ships. Several studies compare marine fuels using LCA frameworks, assessing emissions, energy input, and pollution potential.

One comparative study found that green hydrogen and green ammonia offer the highest GHG reduction potential compared to conventional fuels, although both have high production energy demands and associated costs (Tomos et al., 2024). LNG, while cleaner during combustion, suffers from methane slip, significantly weakening its overall climate benefit. It has also been highlighted that the common operation of LNG feeder vessels to circle around burning boil-off gas will add to the overall emissions of these types of ships (Hörteborn and Hassellöv, 2023). Another LCA study combined environmental and economic sustainability metrics and developed fuel selection “maps” based on emissions and policy scenarios. It found that while hydrogen and ammonia can meet decarbonisation targets, they incur higher lifecycle costs under current market conditions (Karvounis et al., 2024).

The assessment of various hydrogen production methods and different representative fuel cell systems showed that the fuel production pathways have a high impact in the well-to-wake LCA, where the well-to-tank results are much greater than the tank-to-wake values (Jang et al., 2022).

Transoceanic vessel applications of alternative fuels were evaluated in one study, which showed that renewable ammonia outperformed hydrogen and fossil fuels in several environmental impact categories, including global warming potential and aquatic toxicity (Bicer and Dincer, 2018). A well-to-wake assessment of 14 marine fuels highlighted ammonia's low emissions during combustion, especially the absence of CO₂ and SO_x, but noted significant upstream impacts, particularly in toxicity and eutrophication categories, depending on the production method (Zincir and Arslanoğlu, 2024).

Several studies specifically examine ammonia's lifecycle performance in real-world ship applications. These cases provide valuable insights into both environmental impacts and system integration challenges. A study on a short-sea general cargo vessel demonstrated that green ammonia could reduce GHG emissions by up to 79 % compared to marine diesel. However, the analysis highlighted high NO_x emissions, which necessitate the use of after-treatment systems such as SCR. Blue ammonia, although less effective, was still sufficient to meet IMO's 2030 targets (Zincir, 2022).

A techno-economic study of an ammonia-fuelled container ship using solid oxide fuel cells (SOFCs) and onboard ammonia cracking showed that the configuration could achieve zero CO₂ emissions during operation. The results also identified challenges related to system

complexity, ammonia availability, and storage requirements (Wu et al., 2022). Another LCA study was performed on a ferry using an ammonia-hydrogen blend and integrated SCR for NO_x control. The system achieved zero carbon emissions with approximately 42 % energy efficiency, highlighting both technical viability and compliance with decarbonisation targets (Sánchez et al., 2023).

For offshore support vessels used in wind energy projects, a comparative study using LCA and machine learning techniques found that green ammonia had lower impacts than LNG in categories such as global warming potential and eutrophication. Nonetheless, operational risks related to fuel handling and emissions control remained significant (Ahmed et al., 2023). Ammonia use in luxury vessels was evaluated through a case study involving a mega-yacht powered by a PEM fuel cell system. The onboard ammonia cracking technology was found to deliver strong environmental benefits, although the system's energy autonomy and spatial demands limited its broader applicability (Micoli et al., 2024).

2.3. Ship integration consideration

Few studies explicitly integrate vessel design choices, particularly new-build versus retrofitted configurations, into LCA frameworks. Yet these considerations have major implications for fuel efficiency, emissions, and environmental trade-offs.

A study focusing on retrofitting ammonia engines into existing bulk carriers noted that while technically feasible, the process introduces inefficiencies and may increase operational emissions unless countered with design improvements (Ejder and Arslanoğlu, 2022). A comparison of retrofit and new-build configurations for ammonia-powered container ships using SOFCs showed that new vessels had better emissions and cost profiles due to optimized tank placement and propulsion integration. Retrofitting offered faster implementation but entailed greater trade-offs in terms of energy use and design constraints (Wu et al., 2022).

Additional analysis of general cargo ships also highlighted the impact of structural adjustments on LCA outcomes, especially when larger or multiple tanks are required for storing low-density fuels like ammonia (Zincir, 2022). Ammonia retrofitting typically involves the installation of pressurized or cryogenic storage tanks, resulting in additional structural modifications, reduced cargo space, and increased fuel consumption due to higher displacement. These factors are seldom included in cradle-to-grave LCA models but can significantly affect lifecycle performance. Ammonia has been considered in one study evaluating the carbon footprint by using LCA and further works by taking into account of the storage system and other impact categories will bring more beneficial to the industry (Chalaris et al., 2022). Another research work assessed ammonia/hydrogen-driven marine propulsion by evaluating how much emission and environmental impact are brought by alternative fuels comparing with traditional fuels. It has been mentioned some significant issues requires attention including fuel infrastructure and safety etc.; therefore, no storage system is under consideration (Dong et al., 2024). Similarly in one report regarding the life cycle GHG emission study on applying ammonia as a marine fuel, the focus of the study is on the fuel side instead of inclusion of storage tanks (Schuller et al., 2024).

Despite these insights, most LCA studies continues to focus on operational emissions and fuel production, with relatively few considering ship-level modifications or end-of-life impacts. This gap underscores the need for more holistic lifecycle approaches that integrate design, retrofitting, and operational data into emissions modelling (Tomos et al., 2024). This study takes a comprehensive approach by evaluating emissions not only from fuel production and ship operation but also from the entire life cycle of ammonia storage tanks, including their material extraction, manufacturing, use and end-of-life stages.

3. LCA methodology

The application of LCA to ammonia as a marine fuel involves a systematic evaluation of all its stages, including production, transportation, storage, utilization in combustion engines, and the disposal or recycling of fuel storage systems (Fig. 1). This assessment follows ISO 14040/14044 standards and considers key phases critical to environmental impact analysis (ISO, 2006a, 2006b)

- Goal and Scope Definition
- Inventory Analysis
- Life Cycle Impact Assessment (LCIA)
- Interpretation

This research study aims to conduct a LCA study of ammonia-fuelled ships that store and transport ammonia onboard. The study is structured around several specific objectives to ensure a comprehensive evaluation of the environmental impacts associated with a demonstrator and desktop study ships. These objectives are designed to provide a detailed analysis of the entire life cycle of ships and their storage systems, with a focus on key environmental concerns and appropriate assessment methodologies:

1. Evaluate the environmental impact of various types of marine vessels: This objective assesses the overall environmental impact of various types of ships, focusing on ammonia as a marine fuel. It examines both traditional and composite storage tank solutions, as well as the demonstrators and desktop studies developed within the project. The goal is to evaluate the environmental benefits, trade-offs, and challenges associated with transitioning from conventional marine fuels to ammonia-based systems, providing insights into their sustainability performance. The functional unit is defined as the entire lifespan of the ship, from cradle to grave, and the LCA results represent the total environmental impacts over the ship's full life cycle.
2. Cover all activities from cradle to grave for ships and storage tanks: The LCA follows a cradle-to-grave approach, covering all lifecycle stages of ammonia-fuelled ships and their storage tanks. This includes material extraction, manufacturing, fuel production, transportation, storage, vessel operation, and end-of-life processes such as decommissioning or recycling. By considering the entire lifecycle, this objective ensures a comprehensive understanding of

environmental impacts at each stage, highlighting areas for improvement and optimization.

3. Quantify life cycle emissions: A critical aspect of the LCA is quantifying key pollutant emissions across the lifecycle of ammonia-fuelled vessels. The primary pollutants under consideration include CO₂, SO_x, NO_x, and particulate matter (applicable only during utilization). This quantification provides a detailed breakdown of emissions at each stage, serving as a foundation for impact assessment and establishing the overall environmental footprint of the system.
4. Apply LCA methods and determine the impacts of pollutants: To analyse the identified pollutants, established LCA methodologies such as CML will be applied. These methods enable categorization and evaluation of environmental impacts across key indicators, including GWP, AP, EP and POCP. GWP evaluates the contribution of emissions to climate change by measuring the heat-trapping effect of greenhouse gases over a set time horizon. AP assesses the release of acidic compounds that lead to ecosystem damage through acid rain and soil degradation. EP quantifies the nutrient enrichment of water bodies, which can cause algal blooms and oxygen depletion harmful to aquatic life. POCP measures the formation of ground-level ozone from precursor emissions like NO_x and VOCs, contributing to smog and air quality deterioration. These ensure that the environmental consequences of emissions are measured scientifically, providing meaningful insights into the long-term effects of ammonia-fuelled ships.
5. Conduct sensitivity analysis to assess parameter influence on LCA outcomes: Sensitivity analysis will be conducted to evaluate how variations in key parameters—such as fuel production techniques, operational efficiencies, and storage technologies—affect the overall LCA results. This analysis helps identify critical factors influencing the environmental performance of ammonia-fuelled ships, enabling informed decision-making and optimization strategies for future developments.
6. Carry out uncertainty analysis to determine confidence levels in data collection: Given the complexity of LCA and data variability, an uncertainty analysis will quantify confidence levels in data collection and analysis. This step ensures the reliability and robustness of the LCA results by accounting for potential variability in assumptions, data sources, and model inputs. The uncertainty analysis helps stakeholders interpret the precision of findings and highlights areas where further research or more accurate data may be needed.

These objectives collectively ensure that the study provides a thorough, data-driven assessment of the environmental impacts of ammonia-fuelled ships, offering valuable insights to support sustainability and emissions reduction efforts in the maritime industry.

The scope of this LCA study covers both the demonstrator and five desktop studies. Fig. 2 encompasses ammonia fuel types and tank storage systems, covering emissions, energy consumption, resource depletion, and waste generation across various life cycle stages: from fuel production and processing to transport, storage, and vessel operation. For storage tanks, the analysis includes construction, operation, maintenance, and end-of-life disposal. This comprehensive approach ensures a complete well-to-wake (WtW) LCA analysis. This study considers both metallic and composite storage tanks. However, aside from ammonia fuel and storage solutions, the LCA does not include auxiliary systems or other conventionally built equipment. The scope also defines data requirements, assumptions, and inherent limitations, ensuring that the LCA remains targeted, transparent, and relevant for applications such as product development, policy-making, or environmental reporting. Additionally, a well-defined scope facilitates comparative analysis of alternative technologies or processes, such as traditional versus advanced fuel storage systems, helping to identify the most sustainable options.

For the desktop ship studies, this work considers various ship types to provide a comprehensive overview of the differing design and

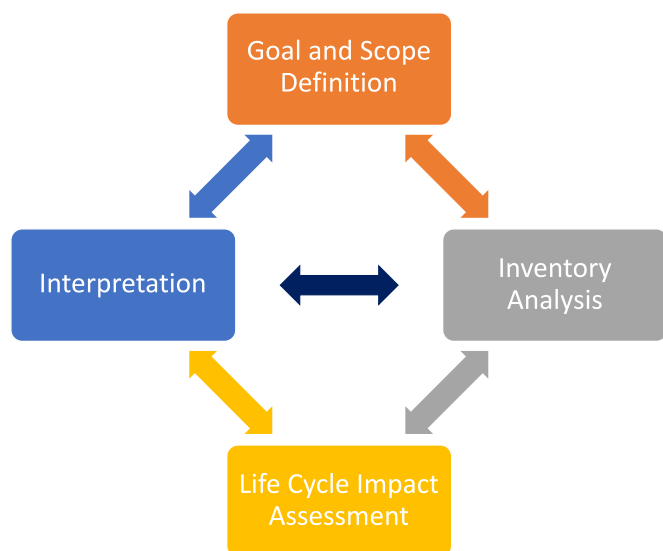


Fig. 1. LCA framework.

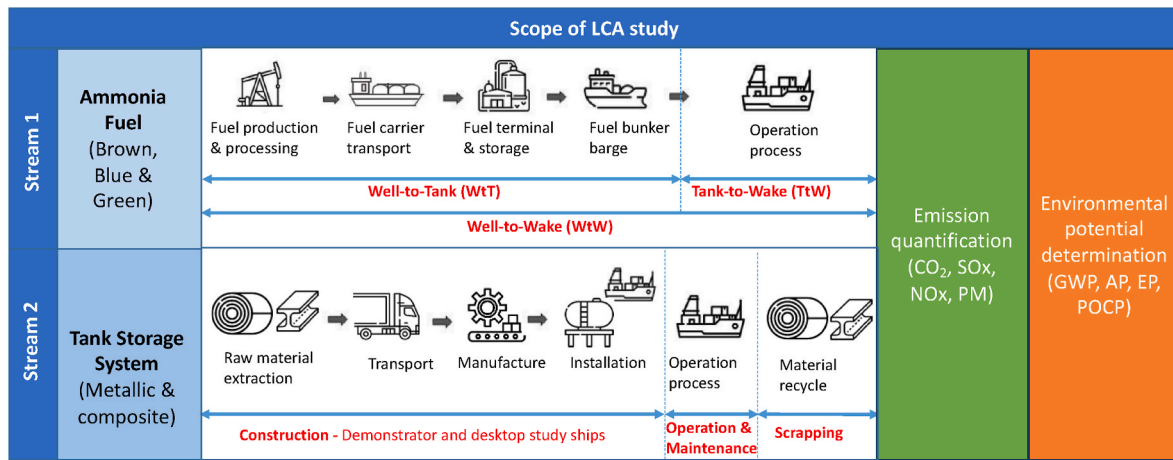


Fig. 2. Scope of the LCA study.

performance characteristics related to ammonia storage tanks. The results will highlight the LCA performance of these tanks, illustrating their contribution to the overall environmental impact of the ships by reflecting both their functional role and the environmental implications of their design and development.

The CML methodology, developed by Leiden University, is a widely recognized approach for conducting LCA and is applied in this study to assess environmental impacts systematically (CML - Department of Industrial Ecology, 2016; Huijbregts, 2016). It provides a structured framework for evaluating the environmental impacts of a product or process throughout its life cycle, from raw material extraction to disposal or recycling. It focuses on quantifying impacts across various categories using scientifically validated models. Key Features of the CML methodology are:

1. The CML methodology, used in this study for impact assessment, offers a structured and scientifically robust approach to evaluating environmental effects across the full life cycle of ships. It operates through a midpoint-oriented framework, concentrating on stressors such as emissions and resource use, rather than endpoint consequences like biodiversity loss or human health outcomes. Environmental impacts are categorized under key indicators such as global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and photochemical ozone creation potential (POCP), among others. CML applies characterization factors to translate emissions, such as CO₂ and methane, into comparable metrics like CO₂ equivalents, thereby facilitating consistent impact quantification. The model primarily uses global or European baseline conditions but allows for regional customization where relevant, enabling better alignment with local environmental contexts. Detailed emission quantification is integral to the methodology, capturing inputs and outputs throughout the ship's life cycle. Additionally, normalization and grouping can be employed to contextualize and synthesize results for more informed decision-making, depending on the goals and scope of the analysis.

3.1. Governing equations

Using the specific fuel oil consumption (SFOC) approach, fuel consumption and emissions for a marine engine can be estimated as follows:

$$m_{fuel} = SFOC \times P_{engine} \times t \quad (1)$$

where:

- m_{fuel} = total fuel consumption (kg)

- $SFOC$ = specific fuel oil consumption (g/kWh)
- P_{engine} = engine power output (kW)
- t = operating time (hours)

The total fuel energy input is estimated, and this is used then for the conversion of fuel from traditional fuels (HFO and MDO) to alternative fuel (ammonia):

$$E_{fuel} = m_{fuel} \times LHV \quad (2)$$

where:

- E_{fuel} = fuel energy input (MJ)
- LHV = lower heating value of the fuel (MJ/kg)

Emissions generated from fuel consumption are estimated using emission factors:

$$M_{emission,i} = m_{fuel} \times EF_i \quad (3)$$

where:

- $M_{emission,i}$ = mass of pollutant i (kg)
- EF_i = emission factor for pollutant i (kg/kg fuel)

A generalized governing equation for Life Cycle Assessment (LCA) that incorporates multiple life phases and environmental impact potentials can be expressed as:

$$I_{total} = \sum_p \sum_e \sum_i (M_{p,e,i} \times EPF_{e,i}) \quad (4)$$

where:

- I_{total} = total environmental impact
- p = life cycle phase (e.g., production, transportation, storage, operation, end-of-life)
- e = environmental impact category (e.g., global warming, acidification, eutrophication, photochemical ozone creation)
- i = specific emission (e.g., CO₂, NO_x, SO₂, NH₃, etc.)
- $M_{p,e,i}$ = mass of emission i in phase p contributing to impact category e
- $EPF_{e,i}$ = emission potential factor or characterization factor linking i to impact category e

This equation aggregates emissions and resource uses across different life cycle phases while converting them into environmental impact based on impact category characterization factors. It is worth

noting that some of the environmental impact has been collected from published literature, which is directly added to the total environmental impact bypassing the calculation from the above equation.

The assumptions used in this study include:

1. Shipyard processing and electricity data are sourced from the SHIPLCA database, which represents a UK shipyard. This may introduce inaccuracies when applying the data to different shipyards.
2. For the scrapping phase, the same material processing technologies and specifications (e.g., speed and power) were assumed due to a lack of specific information on scrapping yards at this stage.

3.2. SHIPLCA software

The SHIPLCA software is an in-house innovative tool developed as part of the SHIPLYS project (Wang et al., 2020), aimed at enhancing the sustainability of maritime operations through comprehensive life cycle assessment. SHIPLCA allows users to evaluate environmental impacts from design through to decommissioning, considering factors such as materials, construction, operation, maintenance, and end-of-life disposal. Users can input a wide range of parameters, including ship particulars, operational profiles, fuel types, and machinery specifications, ensuring the assessments are tailored to specific operational scenarios. The software calculates various environmental impact metrics, including greenhouse gas emissions, energy consumption, and resource utilization. This data helps users identify environmental hotspots and areas where operational improvements can be made. SHIPLCA is designed with ease of use in mind, providing an intuitive interface that makes it accessible to a broad range of stakeholders, including ship designers, operators, and policymakers. The user-friendly platform facilitates quick data entry and analysis, enabling users to generate insightful reports.

Within the context of the LCA, SHIPLCA can effectively conduct detailed life cycle assessments of NH₃ fuel systems, following the same LCA analysis structure outlined in Chapter 2, including the associated

storage tanks. Fig. 3 illustrates the architecture of the SHIPLCA software. By inputting specific data related to ship designs, operational profiles, and ammonia production methods, users can analyse the environmental impacts across various life cycle stages. This process enables stakeholders to identify areas for improvement, optimize designs for sustainability, and assess the overall feasibility of ammonia as a fuel source. As the maritime industry faces increasing challenges related to environmental regulations and the push for sustainable practices, SHIPLCA provides stakeholders with the tools needed to make informed decisions that support a greener, more sustainable future for shipping, particularly during the transition to ammonia-based fuels. Through its comprehensive assessments and user-friendly design, SHIPLCA fosters innovative solutions that balance operational efficiency with environmental responsibility in the industry.

4. Data collection for ammonia fuel

This section outlines the data collection methods and types of information needed to assess the environmental impacts of NH₃ fuel, along with its storage tanks. This encompasses various aspects, including the types of ammonia produced, energy consumption and CO₂ emissions during production, transportation logistics, storage practices, and characteristics of different storage tank designs.

4.1. Ammonia fuel types

Ammonia can be categorized into three primary types based on the production methods employed and their environmental impacts: brown ammonia, blue ammonia, and green ammonia. Each type has unique characteristics that significantly influence energy consumption, CO₂ emissions, and overall sustainability.

Brown ammonia is produced primarily from fossil fuels, specifically through the Haber-Bosch process, which combines nitrogen from the air with hydrogen derived from natural gas. This method is characterized by high energy consumption and significant CO₂ emissions resulting from fossil fuel combustion.

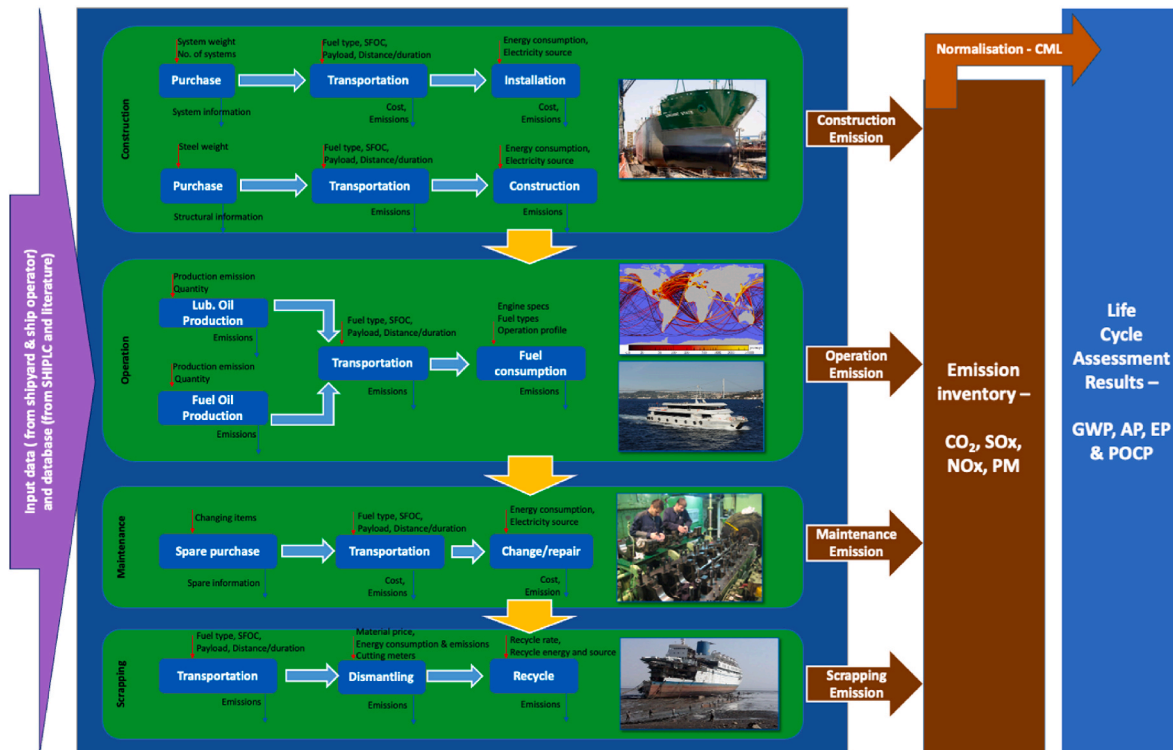


Fig. 3. SHIPLCA software architecture.

Blue ammonia employs a similar production process as brown ammonia but integrates carbon capture and storage (CCS) technologies to mitigate CO₂ emissions. The energy consumption data for blue ammonia production needs to be focused in parallel to the emission generation.

Green ammonia is produced using renewable energy sources, such as wind or solar power, to electrolyze water and generate hydrogen, which is then combined with nitrogen.

4.2. Ammonia production

Ammonia production is an energy-intensive process, and its energy consumption varies depending on the production method. For traditional “brown” ammonia production, which relies on fossil fuels, the energy requirement is approximately 8 MWh per ton of ammonia. However, around 90 % of this energy consumption stems from the production of hydrogen, which is a key input in the ammonia synthesis process. Various feedstocks such as coal, heavy fuel oil, and naphtha can be used for hydrogen production, but these have much higher associated CO₂ emissions compared to natural gas. For instance, coal, heavy fuel oil, and naphtha produce between 2.5 and 3.8 tons of CO₂ per ton of ammonia, while natural gas emits approximately 1.6 tons of CO₂ per ton of ammonia (Royal Society, 2020).

Brown ammonia production primarily uses fossil fuels, with natural gas being the most common. The carbon intensity of brown ammonia varies depending on the feedstock, with natural gas being the least carbon intensive. The overall carbon footprint of brown ammonia remains significant, with most of the emissions stemming from the hydrogen production process. Coal, heavy fuel oil, and naphtha contribute significantly higher CO₂ emissions, further exacerbating the environmental impact of brown ammonia production.

Blue ammonia incorporates CCS technologies to reduce its carbon footprint. The energy conversion efficiency of blue ammonia production varies depending on the CCS technology and the level of hydrogen recovery. For instance, post-capture processes with 90 % hydrogen recovery yield an energy conversion efficiency of 76 %, while syngas capture with 70 % hydrogen recovery achieves 70 %. Other recovery configurations offer efficiencies between 72 % and 73 %, depending on the capture process used (Leeds City Gate, 2016). These efficiencies highlight the trade-offs between energy use and carbon reduction in blue ammonia production.

Green ammonia is produced using renewable energy sources, typically through water electrolysis to generate hydrogen. The energy consumption for hydrogen production in green ammonia processes ranges from 4.3 to 7.5 kWh per cubic meter of hydrogen (equivalent to 8.4–14.7 MWh per ton of ammonia) (Ursúa et al., 2012). Since green ammonia production relies solely on renewable energy, it has the potential to achieve zero CO₂ emissions, making it a highly sustainable alternative to fossil-fuel-based ammonia production.

The CO₂ emissions from ammonia production are closely tied to the energy source used for hydrogen production. For brown ammonia, CO₂ emissions can range between 2.5 and 3.8 tons of CO₂ per ton of ammonia when using coal, heavy fuel oil, or naphtha, while natural gas produces 1.6 tons of CO₂ per ton of ammonia. In the case of blue ammonia, CO₂ emissions are significantly reduced due to CCS technologies. Depending on the CCS configuration, emissions can range from 39.8 to 59.4 g/kWh (equivalent to 0.2–0.3 tons of CO₂ per ton of ammonia). For example, post-capture processes with 90 % hydrogen recovery result in CO₂ emissions of 57.2 g/kWh (0.3 tons of CO₂ per ton of ammonia), while syngas capture with 90 % hydrogen recovery can achieve emissions as low as 39.8 g/kWh (0.2 tons of CO₂ per ton of ammonia). Green ammonia, on the other hand, produces zero CO₂ emissions, making it the most environmentally friendly option for ammonia production.

4.3. Ammonia transportation

Transportation plays a vital role in the overall environmental impact of ammonia fuel.

For pipeline transportation (Huib et al., 2003), the emissions and energy consumed for transporting ethylene and propylene within the EU is used in this study, as shown in Table 1, Tables 2 and 3. The usage of this data is due to a lack of ammonia transportation data and this chemical transportation can be a good indication for the energy and emission assumption from ammonia transportation via pipeline.

4.4. Ammonia storage and bunkering

Effective storage and bunkering practices are essential for maintaining the safety and integrity of ammonia fuel. This section will explore key storage methods, including loading and unloading processes, liquefaction, and overall ammonia storage practices.

The energy consumption for loading and unloading ammonia is relatively minimal compared to other stages of the ammonia lifecycle. According to Al-Breiki and Bicer (2020), the energy required for this process is approximately 0.00196 MJ per kilogram of ammonia. This low energy usage reflects the efficiency of modern loading and unloading technologies, particularly in well-optimized industrial operations. Although the energy requirement is small, it still contributes to the overall energy footprint of ammonia logistics and should be considered in life cycle assessments of ammonia as a fuel or industrial product.

The storage of ammonia involves two key energy-consuming processes: liquefaction and the maintenance of storage conditions. Liquefaction is required to convert ammonia into its liquid form for more efficient storage and transport. This process consumes about 0.02 kWh per kilogram of ammonia, which ensures that ammonia can be stored at low temperatures in a condensed state.

Once ammonia is liquefied, the energy required to maintain stable storage conditions is slightly higher, at around 0.12 kWh per kilogram of ammonia. This energy is used to maintain the low temperatures necessary to keep ammonia in its liquid form, preventing it from vaporizing and maintaining its safety and usability over long periods. Ammonia storage at high pressure is not considered, while ammonia stored at low temperature is preferred, which is in line with the latest IMO interim guidelines, 2024 (CCC10) (IMO, 2024). Together, the liquefaction and storage processes represent a significant portion of the energy required for ammonia’s handling and logistics, making them important factors in assessing its environmental and economic viability as an alternative fuel (Bañares-Alcántara et al., 2015).

4.5. Emissions of ammonia

4.5.1. Well to tank (WTT) emissions

The well-to-tank (WtT) emissions of ammonia cover the full range of activities from raw material extraction (the “well”) through production, transportation, and storage on shore facilities, up to the point where ammonia is ready for use (the “tank”). These emissions vary significantly depending on the production pathway, whether brown, blue, or green ammonia. These pathways differ in their energy sources and carbon management strategies, affecting the overall environmental impact. Tables 4–8 indicate the emission factors for various types of ammonia fuel, combining all the data collected in the previous sections.

Table 1
Emission factors for pipeline transportation.

Transportation emission factors	Emissions				
	CO ₂	NO _x	PM10	SO ₂	VOC
Emission factor (g/MJ)	60.00	0.11	0.02	0.29	0.01

Table 2
Energy consumption for pipeline transportation.

Energy consumption (MJ/ton-km)	
Best	0.11
Worst	0.18
Average	0.14

Table 3
Emission types for pipeline transportation.

Transportation Emission	Emissions (g/ton-km)				
	CO ₂	NO _x	PM10	SO ₂	VOC
Best	6.60	0.01	0.0022	0.03	0.0011
Worst	10.80	0.02	0.0036	0.05	0.0018
Average	8.40	0.02	0.0028	0.04	0.0014

Table 4
WtT emission impact for brown ammonia (Coal, HFO, Naptha).

Emission impact	Amount	Unit
GWI	7.67E+00	kg CO ₂ e/kg fuel
AI	2.02E-04	kg SO ₂ e/kg fuel
EI	3.92E-03	kg PO ₄ ³⁻ e/kg fuel
POCI	7.13E-05	kg C ₂ H ₄ e/kg fuel

Table 5
WtT emission impact for brown ammonia (Natural Gas).

Emission impact	Amount	Unit
GWI	2.16E+00	kg CO ₂ e/kg fuel
AI	2.02E-04	kg SO ₂ e/kg fuel
EI	2.37E-04	kg PO ₄ ³⁻ e/kg fuel
POCI	3.56E-05	kg C ₂ H ₄ e/kg fuel

Table 6
WtT emission impact for blue ammonia (Post capture).

Emission impact	Amount	Unit
GWI	6.87E-01	kg CO ₂ e/kg fuel
AI	2.02E-04	kg SO ₂ e/kg fuel
EI	2.37E-04	kg PO ₄ ³⁻ e/kg fuel
POCI	3.56E-05	kg C ₂ H ₄ e/kg fuel

Table 7
WtT emission impact for Blue Ammonia (Syngas capture).

Emission impact	Amount	Unit
GWI	5.93E-01	kg CO ₂ e/kg fuel
AI	2.02E-04	kg SO ₂ e/kg fuel
EI	2.37E-04	kg PO ₄ ³⁻ e/kg fuel
POCI	3.56E-05	kg C ₂ H ₄ e/kg fuel

Table 8
WtT emission impact for green ammonia.

Emission impact	Amount	Unit
GWI	3.00E-02	kg CO ₂ e/kg fuel
AI	2.75E-05	kg SO ₂ e/kg fuel
EI	7.15E-06	kg PO ₄ ³⁻ e/kg fuel
POCI	1.54E-06	kg C ₂ H ₄ e/kg fuel

The GWP, AP, EP and POCP emission impacts (GWI, AI, EI, POCI) are presented.

4.5.2. Tank to wake (TTW) emissions

The tank-to-wake (TtW) emissions of ammonia refer to the environmental impact that occurring during its use as a fuel, specifically from the point it leaves the on-board storage tank to its combustion or utilization in an engine. Unlike fossil fuels, ammonia is a carbon-free molecule, meaning that it does not directly emit CO₂ when burned. However, ammonia combustion can produce other pollutants, such as NO_x, which are harmful to the environment and human health. Advanced combustion technologies, such as selective catalytic reduction (SCR) systems, can be employed to mitigate NO_x emissions, reducing their impact significantly to meet IMO Tier III NO_x emission regulations (Table 9) (Mckenney, 2023). It is assumed in this study sufficient measures will be adopted to meet this regulation so that the NO_x emission can be estimated based on the target emission level of 2g/kWh. Additionally, if ammonia leaks or is unintentionally released, it can contribute to air pollution and pose risks due to its toxicity. Subject to data availability on ammonia slip from ammonia engines (which will be released soon) and considering a safe design, ammonia release is not considered. Overall, ammonia's TtW emissions are considered relatively low in terms of GHGs compared to conventional fuels, but effective NO_x management and safety measures are crucial for minimizing its environmental footprint during use. One of the benefits of ammonia as a marine fuel is that it does not produce SO_x or PM emissions during combustion. The normalised target levels for emissions are included in the same table.

The environmental impacts of the emissions presented in Table 9, along with their corresponding emission indicators, are summarized in Table 10. The indicative emissions for GWP, AP, EP and POCP are CO₂, SO₂, PO₄³⁻ and C₂H₄ respectively. Using the normalised emission quantities and the environmental potentials of each emission, Table 11 presents the normalised tank-to-wake environmental impacts for ammonia in terms of GWP, AP, EP and POCP.

4.6. Case study

This section outlines the diverse range of inputs required for an accurate analysis of the environmental impacts associated with ammonia fuel and its storage tanks. By incorporating detailed vessel-specific data, in particular demonstrator and desktop studies, from NH₃CRAFT project, it is aimed to accurately estimate fuel consumption and emissions generated throughout the different lifecycle stages of these components.

4.6.1. Ship particulars

This includes identifying specific information about the design, dimensions, and operational capabilities of the demonstrator considered in the project (Table 12). Key details such as the ship's size, type, age, and intended use are critical for LCA to understand its performance and fuel efficiency. Parameters such as cargo capacity, cruising speed, and fuel type provide insights into the overall operational profile and its impact on ammonia fuel consumption. The ship particulars for the 5 desktop studies are shown in the following tables (Tables 13–17).

4.6.2. Operational profile and machinery data

The operational profile encompasses the typical routes, speeds, and

Table 9
TtW Emission level for Ammonia.

Emission	Target level	Normalised target level
N ₂ O	0.06 g/kWh	0.00032 kg/kg NH ₃
NO _x	Tier III (≈2 g/kWh)	0.011 kg/kg NH ₃
SO _x	N/A	N/A
PM	N/A	N/A

Table 10
Environmental potentials of emissions compared to emission indicators.

Environmental potentials	GWP	AP	EP	POCP
CO ₂ ^a	1	–	–	–
SO ₂ ^a	–	1.2	–	0.048
PO ₄ ^{3–a}	–	–	1	–
C ₂ H ₄ ^a	–	–	–	1
N ₂ O	265	–	0.27	–
NOx	–	0.5	0.13	0.028

^a These emissions are the emission indicators for the environmental potentials.

Table 11
TtW environmental impact (Normalised TtW emission factors) for ammonia.

Emission impact	Amount	Unit
GWI	8.37E-02	kg CO ₂ e/kg fuel
AI	5.26E-03	kg SO ₂ e/kg fuel
EI	1.45E-03	kg PO ₄ ^{3–} e/kg fuel
POCI	2.95E-04	kg C ₂ H ₄ e/kg fuel

Table 12
Main characteristics of the demonstrator: multi-purpose dry-cargo heavy lift vessel.

Ship particulars	Value	Unit
Overall length	193.9	m
Breadth (moulded)	28.2	m
Depth (moulded)	15.6	m
Draught (moulded)	11.2	m
Deadweight	31,000	ton
Cargo capacity	39,700	m ³
Container capacity	2019	TEU
M/E power (@CSR)	10,458	kW
Engine speed (@CSR)	120	rpm
Service speed (@CSR)	16.8	knot
Endurance	15,000	nautical miles
Years remain in service	17 ^a	Years

^a Calculated based on the ship entering service in 2011, with a life span of 30 years, and for the current year, 2024

Table 13
50,000t DWT Bulk carrier particulars.

Length O.A.	190.633 m
Length B.P.	184.00 m
Breadth (moulded)	32.26 m
Depth (moulded).	17.30 m
Draft (design)	10.15 m
Draft (scantling)	12.00 m
Deadweight	50,000 t DWT

Table 14
50,000t DWT Tanker particulars.

Length O.A.	183.06 m
Length B.P.	175.15 m
Breadth (moulded)	32.20 m
Depth (moulded)	19.10 m
Draft (design)	11.00 m
Draft (scantling)	13.30 m
Deadweight	50,000 t DWT

operational patterns of the ship. This information is vital for estimating fuel consumption and emissions across different operational scenarios. Factors such as voyage length, weather conditions, and port calls can significantly influence fuel use and emissions, which requires a detailed assessment of the ship's operational behaviour. For the demonstrator, different types of fuel and ammonia will be considered for the life cycle

Table 15
2700 TEU Container ship particulars.

Length O.A.	186.0 m
Length B.P.	177.0 m
Breadth (moulded)	34.8 m
Depth (moulded)	17.9 m
Draft (design)	8.5 m
Draft (scantling)	11.00 m
Total container capacity	2746 TEU
Container capacity on deck	1660 TEU
Container capacity in hold	1086 TEU

Table 16
1500 RoPax ferry particulars.

Length O.A.	145.9 m
Length B.P.	133.5 m
Breadth (moulded)	23.2 m
Draft (design)	5.7 m
Draft (scantling)	5.9 m
Deadweight	2300 ton

Table 17
Small double ended ferry particulars.

Length O.A.	43.5 m
Length B.P.	39.99 m
Breadth (moulded)	12.2 m
Breadth (extreme)	12.3 m
Draught (maximum)	1.74 m
Depth (moulded)	3 m
Deadweight	95 ton

analysis in order to showcase the environmental impacts when changing to different fuels.

Data related to the ship's machinery, including engines, generators, etc., is essential for evaluating fuel efficiency and emissions. This includes specifications on:

- Engine Type: Information on the type of engines used (e.g., dual-fuel, gas engines) and their operational efficiencies.
- Power Output: Details on the rated power output of the machinery, which will help estimate the energy requirements during different operational stages.
- Performance Metrics: Data on fuel consumption rates, thermal efficiencies, and emissions profiles for different machinery under varying load conditions.

In this study, for a simplified estimation, the annual fuel oil consumption of the original ships was used (Table 18). It is used to estimate the TtW emissions for both the original ship using fossil fuel (HFO/MDO) and the ammonia retrofit ship. The ammonia fuel required is a direct conversion from fossil fuel with the same energy amount from the lower heating value of fuels (MDO: 42.78 MJ/kg, ammonia 18.8 MJ/kg)

4.6.3. Tanks properties

Table 19 provides detailed information on the capacities of ammonia storage tanks used aboard ammonia-fuelled ships. These storage tanks are critical for safely storing and transporting ammonia as a marine fuel. Also, the table outlines several key parameters, including the tank volume, which indicates the amount of ammonia that can be stored in each

Table 18
Annual fuel oil consumption (ton) of the demonstrator ship.

Operational condition	M/E	Prop. A/E	Prop. Boiler	Total
Laden	3976.3	505.2	1.5	4483.0
Ballast	402.3	56	0.3	458.6

Table 19
Storage tank properties of the demonstrator ships.

Tank types	Material	Weight (ton)	Volume (m ³)
Metallic tanks	Low-Temperature Carbon Steel	191	690
Composite tanks	Glass fibre	19	80

tank. This volume is a crucial factor for determining the operational range of the ship, as larger tanks enable the vessel to carry more fuel and thus travel longer distances between refuelling.

In addition to volume, the weight of the tanks is also specified in Table 18. This includes both the weight of the tank structure itself and the ammonia it contains. The weight is an important consideration for ship stability and performance, as heavier tanks can affect the ship's draft, balance, and fuel efficiency. Managing the weight distribution on board is essential for maintaining the ship's operational efficiency and safety.

Lastly, Table 19 describes the materials used in the construction of the tanks. Ammonia is a highly corrosive substance, and the choice of materials is vital to ensure the long-term durability and safety of the tanks. Common materials for ammonia tanks include stainless steel and specialized composite materials, which are resistant to corrosion and capable of withstanding the low temperatures required to keep ammonia in its liquid state. The materials must also meet stringent safety and regulatory standards to prevent leaks and other hazards associated with ammonia storage.

Together, these parameters—volume, weight, and materials—provide a comprehensive view of the design and performance characteristics of ammonia storage tanks on ammonia-fuelled ships. The data helps evaluate the LCA performance of the storage tanks in this study, reflecting both their functionality and the environmental impact of their design and development. For desktop studies, the tank details are presented in Table 20.

4.6.4. Material specifications

Understanding the material specifications of ammonia fuel storage tanks is essential for assessing both their performance and safety. This evaluation includes not only the types and quantities of materials used in the previous section but also the associated environmental impacts, such as emissions during steel and glass fibre production (Burchart-Korol, 2013; PwC, 2023), as summarized in the following tables (Tables 21 and 22). It is observed that the GWI, AI and EI of steel production are lower than glass fibre production; however, the POCl comparison results show the opposite.

4.6.5. Shipyard data

Data from shipyards involved in the new-building (containership) or retrofitting of ships (other vessels) for ammonia fuel usage is essential for understanding the feasibility and potential challenges associated with implementing ammonia as a fuel source. This includes:

Table 20
Tank details of the desktop study ships.

Ship types	Weight (ton)
50,000t DWT Bulk carrier	275 (Steel)
50,000t DWT Tanker – Design Variant 1	369 (Steel)
50,000t DWT Tanker – Design Variant 2	369 (Steel) + 4 (Glass fibre)
2700 TEU Container ship	128 (Steel)
1500 RoPax ferry	121 (Steel)
Small double ended ferry inland waterways	4.2 (Steel)
Multi-purpose dry-cargo heavy lift vessel (Demonstrator)	191 (Steel) +19 (Glass fibre)

Table 21
Emission factors of steel production.

Emission impact	Amount	Unit
GWI	1.70	kg CO ₂ e/kg steel
AI	4.81E-03	kg SO ₂ e/kg steel
EI	0.81E-03	kg PO ₄ ³⁻ e/kg steel
POCl	8.12E-03	kg C ₂ H ₄ e/kg steel

Table 22
Emission factors of glass fibre production.

Emission impact	Amount	Unit
GWI	2.02	kg CO ₂ e/kg GF
AI	8.21E-03	kg SO ₂ e/kg GF
EI	1.03E-03	kg PO ₄ ³⁻ e/kg GF
POCl	6.45E-03	kg C ₂ H ₄ e/kg GF

- Construction Techniques: Insights into the construction methods used for building or modifying ships to accommodate ammonia fuel systems, including any specific challenges or innovations.
- Timeline and Costs: Information on the timelines and costs associated with building or retrofitting ships for ammonia fuel use, which will help inform economic assessments.

Subject to data availability, the existing data (Tables 23 and 24) from SHIPLCA software was adopted for the LCA study.

5. Results and discussion

5.1. Demonstrator

The results of the LCA study for the demonstrator considering different ammonia fuel types as well as tank materials (metallic and composite) are presented in Fig. 4.

The procedure are summarized as follows:

- Section 3.1 presents the governing equations relevant to the estimation of environmental impact including equations for calculating fuel consumption and environmental impact.
- Section 4 provides the necessary input data, covering fuel types and tank materials.
- Using the governing equations and the collected data, the environmental impact results are obtained.

The results reveal that brown ammonia, particularly the one produced from coal, has the highest GWI, at 894,536 tons CO₂e. This alarming figure highlights the substantial carbon emissions associated with coal-based ammonia production, posing significant challenges in mitigating climate change. In contrast, brown ammonia produced from LNG shows a markedly lower GWI of 467,189 tons CO₂e. While LNG is less carbon-intensive than coal, it still contributes significantly to greenhouse gas emissions, indicating the need for cleaner alternatives.

The LCA results for blue ammonia, produced with CCS, show a notable reduction in GWI. The post-CCS production method (blue post) results in 100,483 tons CO₂e, while the syngas CCS (blue syngas) approach further reduces this figure to 77,377 tons CO₂e. These findings highlight the effectiveness of CCS technologies in decreasing the carbon footprint of ammonia production, making blue ammonia a more viable option in the transition to a low-carbon economy.

The lowest GWI is observed for green ammonia, which has a GWI of just 24,974 tons CO₂e. This stark contrast emphasizes the potential of green ammonia produced from renewable energy sources to serve as a sustainable solution in decarbonizing energy systems. The significantly lower emissions from green ammonia illustrate its potential as a future fuel, particularly for maritime applications where reducing carbon

Table 23
Steel processing data.

Processing	Cutting	Bending	Welding	Blasting	Coating	Cleaning
Speed unit/hour	0.72 m	1 ton	24 m	57.6 m ²	600 m ²	
Power requirement (kW)	6.5	50	9.1	160	160	160

Table 24
Electricity data.

Grid mix electricity	Value	Units
GW	1.23E-01	kg CO ₂ e/kWh
AI	3.52E-04	kg SO ₂ e/kWh
EI	3.19E-05	kg PO ₄ ³⁻ e/kWh
POCI	2.25E-05	kg C ₂ H ₄ e/kWh

emissions is crucial.

When examining AI, EI and POCl, the results reveal consistent values across all ammonia types. This uniformity suggests that while the production pathways influence GWI significantly, the acidification, eutrophication, and photochemical impacts are less variable. This indicates that further improvements in these areas may be more closely linked to overall production methods and emission control technologies rather than the feedstock alone.

The LCA results highlight a clear gradient in the environmental impacts of ammonia production methods, with green ammonia emerging as the most sustainable option. The GWI of brown ammonia (coal) is about 33 times higher than that of green ammonia and even for brown ammonia (LNG), the GWI is about 10 times higher than green ammonia. This underscores the urgent need to transition towards cleaner production pathways. As the global community intensifies efforts to combat climate change, the findings from this LCA study can guide policymakers and industry stakeholders in making informed decisions about ammonia production and its role in future energy systems.

5.2. Desktop studies

The LCA study for desktop ships is focused on the storage tanks only, as the overall benefits of the ammonia-fuelled vessels have already been clearly illustrated for the demonstrator vessel. The operational profiles of the desktop study vessels are collected from NH3CRAFT project (Table 25) (NH3CRAFT, 2024). Therefore, with the provided tank configurations, i.e. volume, weight and materials, the LCA performances for different tanks for desktop study ships are summarized and presented in Table 26 and Fig. 5.

The primary observation is that GWI serves as the key environmental indicator (unit is ton CO₂e) in these studies, significantly surpassing the values of other categories (unit is kg indicative emissions equivalent). For tanks of the same type, the results will show a linear increase or decrease in emissions based on the weight of the tanks. Furthermore, when considering two different tank types in case ships, such as steel and composite, the variations in environmental impact values are minimal and do not diminish the dominant influence of GWI in the overall LCA performance.

5.3. Sensitivity and uncertainty analysis

The results from the sensitivity analysis of various fuel types shown in Table 27, reveal how changes in the fuel composition can significantly affect the environmental impact metrics of GWI, AI, EI, and POCl. The data provides critical insights into the environmental implications associated with different fuels utilized in maritime applications.

The GWI varies dramatically among fuel types. Brown ammonia from coal has the highest GWI at 1.96E+06 tons CO₂e, indicating a severe impact on climate change. In contrast, green ammonia stands out with a significantly lower GWI of 5.92E+04 tons CO₂e, underscoring its

potential as a sustainable alternative. The other brown ammonia variant from LNG also exhibits substantial GWI values of 5.87E+05 tons CO₂e, reinforcing the necessity for transitioning to greener fuels.

HFO and MDO cases have GWI of 3.01E+05 and 3.08E+05 tons CO₂e, respectively, which are still high but lower than that of brown ammonia. This highlights the potential for improving the environmental profile of conventional marine fuels by exploring alternative options.

The AI figures reveal that HFO and MDO have significantly higher acidification impact at 5320 tons SO₂e, compared to all ammonia fuel types, which consistently present an AI of 1400 tons SO₂e. This finding indicates that while ammonia fuels may have a relatively lower GWI, they still contribute to acidification, although to a lesser extent than conventional marine fuels. The increased AI associated with HFO and MDO raises concerns about their potential to contribute to acid rain and related environmental issues.

Eutrophication impact remains consistent across all fuel types, with HFO and MDO presenting an EI of 569 tons PO₄³⁻e, while the ammonia fuels exhibit EI ranging from 372 to 1350 tons PO₄³⁻e. These variations suggest that transitioning to ammonia as a fuel from coal-based production may significantly worsen eutrophication impacts and make it a more environmentally friendly option in terms of nutrient loading in aquatic systems, while utilising cleaner and greener production of ammonia.

When it comes to POCl, HFO/MDO shows the highest value at 282 tons C₂H₄e. In contrast, ammonia fuel types exhibit lower values from 79 to 96 tons C₂H₄e across the board. This indicates that ammonia fuels have a reduced potential for contributing to photochemical ozone formation, further reinforcing their environmental advantages.

In addition to the sensitivity analysis of fuel types, Table 26 primarily contributes to the sensitivity analysis of desktop studies, considering factors such as the amount of fuel stored, consumed, and transported, as well as tank type, materials used, and ship type.

The sensitivity analysis clearly illustrates that different fuel types have varying degrees of GWI, AI, EI, and POCl. The substantial differences in GWI between brown ammonia and green ammonia highlight the importance of transitioning to cleaner alternatives. While the acidification and eutrophication potentials are relatively lower for ammonia fuels, the overall findings suggest that ammonia, particularly green ammonia, presents a more sustainable option for maritime applications. This analysis provides essential insights that can guide fuel selection and inform strategies aimed at reducing the environmental impact of shipping activities.

Ammonia as a marine fuel is a clear option for sustainable energy, but its adoption faces several operational challenges and regulatory considerations when compared to traditional fuels:

- Operational Challenges
 - Toxicity and Safety Risks

Ammonia is highly toxic and corrosive, requiring special handling to protect crew, cargo, and the environment. It poses acute health risks via inhalation or skin contact and requires gas detection, ventilation systems, and emergency response protocols beyond what is needed for conventional fuels.

- Combustion and Engine Technology

Ammonia has poor ignition properties, low flame speed, and narrow flammability limits, making direct combustion challenging. Engine

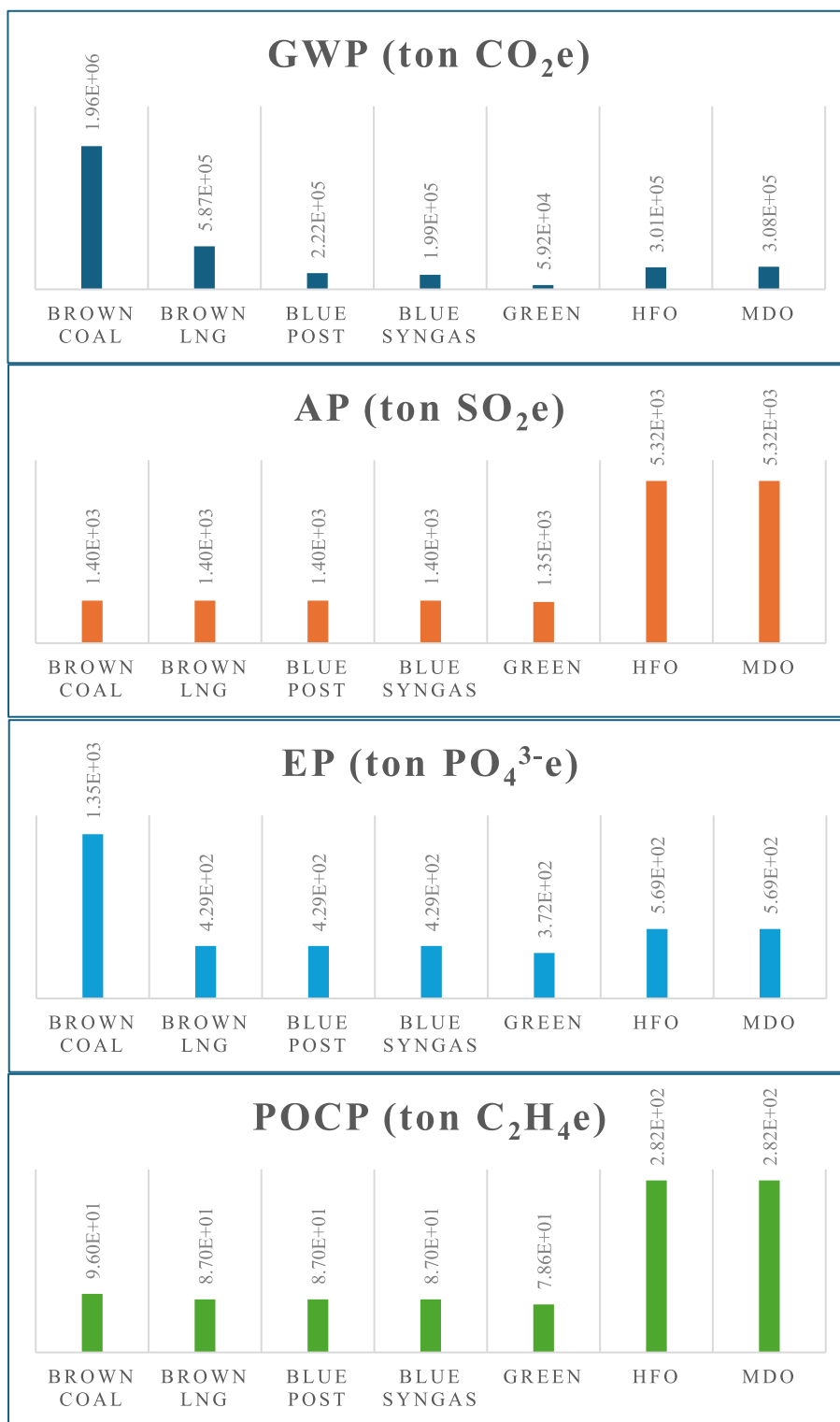


Fig. 4. LCA performance of the demonstrator (fuel and tank).

modifications or dual-fuel systems (e.g., ammonia–diesel pilot) are required, and combustion stability must be addressed to avoid issues like incomplete combustion or NO_x formation.

- Energy Density and Storage

Ammonia has lower volumetric and gravimetric energy density than conventional marine fuels. As a result, ships require larger or more

complex storage systems (pressurized or refrigerated tanks), which can reduce cargo capacity and increase system complexity.

- Bunkering and Infrastructure

Unlike conventional fuels, ammonia bunkering infrastructure is currently lacking in most ports. Its toxicity demands strict handling protocols, dedicated pipelines, and compatible bunkering equipment, all

Table 25
Operational profile of desktop study ships.

Sample ship	Cruising range	Actual operational range
50,000 DWT bulk carrier	3600 nm (oil mode) 5300 nm (gas mode)	1680 nm
50,000 DWT tanker	18,300 nm	4370 nm
2700 TEU Container ship	15,000 nm	4320 nm
1500 RoPax ferry	1820 nm	650 nm
Small double ended ferry inland waterways	830 nm	465 nm

of which are still under development or in pilot stages.

- Corrosiveness

Ammonia is corrosive to several common metals used in marine fuel systems. Special materials and coatings are required for pipelines, tanks, and engine components to ensure durability and prevent leakage.

Table 26
LCA performance of desktop study ship (tank only).

Ship types	Tank material	Weight (ton)	GWI (ton CO ₂ e)	AI (kg SO ₂ e)	EI (kg PO ₄ ³⁻ e)	POCI (kg C ₂ H ₄ e)
50,000 DWT bulk carrier	Metallic	275	618.35	1754.47	261.73	2257.63
50,000 DWT Tanker - Design variant 1	Metallic	369	830.14	2355.39	351.38	3030.89
50,000 DWT Tanker - Design variant 2	Metallic	369	830.14	2355.39	351.38	3030.89
	Composite	4	8.07	32.81	4.12	25.77
2700 TEU Container ship	Metallic	128	288.37	818.20	122.06	1052.85
1500 RoPax ferry	Metallic	121	273.22	775.21	115.65	997.53
Small double ended ferry inland waterways	Metallic	4.2	9.46	26.83	4.00	34.53
Multi-purpose dry-cargo heavy lift vessel (Demonstrator)	Metallic	191	430.07	1220.25	182.04	1570.19
	Composite	19	38.38	155.99	19.57	122.55

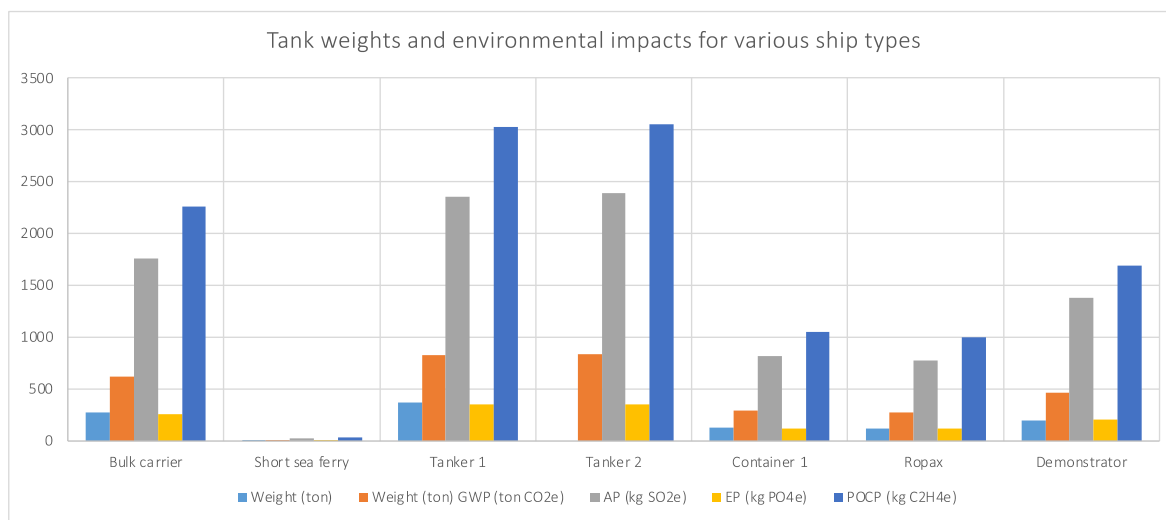


Fig. 5. Tank weights and environmental impacts for various ship types.

Table 27
Environmental impact comparison between various types of ammonia and conventional shipping fuels.

Environmental impact	Brown ammonia - coal	Brown ammonia - LNG	Blue ammonia - Post CCS	Blue ammonia - Syngas CCS	Green ammonia	HFO	MDO
GWI (ton CO ₂ e)	1.96E+06	5.87E+05	2.22E+05	1.99E+05	5.92E+04	3.01E+05	3.08E+05
AI (ton SO ₂ e)	1.40E+03	1.40E+03	1.40E+03	1.40E+03	1.35E+03	5.32E+03	5.32E+03
EI (ton PO ₄ ³⁻ e)	1.35E+03	4.29E+02	4.29E+02	4.29E+02	3.72E+02	5.69E+02	5.69E+02
POCI (ton C ₂ H ₄ e)	9.60E+01	8.70E+01	8.70E+01	8.70E+01	7.86E+01	2.82E+02	2.82E+02

2. Regulatory Perspectives

The IMO is developing guidelines for ammonia as a marine fuel under the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code). However, these are not yet finalized, and current regulatory frameworks are based on risk assessments and case-by-case approvals. Due to the lack of standardized rules, class societies (e.g., DNV, Lloyd’s Register) provide notations and technical guidance for ammonia-fuelled ships. Compliance often involves additional design verification, hazard identification (HAZID), hazard operation, fmea and quantitative risk assessments (QRA). Ports may restrict or delay the approval of ammonia bunkering due to local safety concerns. National or regional regulations may impose strict limitations on ammonia transport, storage, and use within port areas, requiring harmonization for international operations. Although ammonia eliminates CO₂ during operation, its lifecycle emissions must be assessed. Future regulations might incorporate full lifecycle emissions under IMO’s carbon intensity targets, influencing ammonia’s acceptability depending on its production pathway. Regulatory frameworks will need to include updated requirements for crew training, certification, and medical surveillance due to ammonia’s hazards.

To ensure a trustworthy outcome from the LCA study, an uncertainty analysis on the various data collections was carried out. The data collection is through literature review, database application and provision of project-specific data. Goerlandt and Reniers (2016) proposed a qualitative approach to apply strength-of-evidence to develop three levels of data confidence based on expert judgments and assumptions. Three levels are colour-coded as green/yellow/red, which presents strong/medium/low data confidence (Table 28). The same confidence level percentages have been applied to judgments based on expert opinions and assumptions agreed upon by experts.

Based on the defined confidence level and the data collected from the different sources, the confidence levels of the data used in this study are derived and summarized in Table 29. There are 13 groups of data collected following the LCA approach presented in Chapter 2. It is observed that no data is in weak level of confidence; the lowest level of confidence (medium: 69.5) is found for the shipyard working hour assumption, which is difficult to get a more accurate calculation without real data, which varies significantly with the area and the country that the shipyard is located. There are four other data categorized with a medium level of confidence because these data are from published literature and an existing database.

6. Conclusion and recommendations

The comprehensive evaluation of the environmental impacts of ammonia fuel systems and storage solutions, alongside sensitivity analyses of different fuel types, underscores the substantial potential of ammonia as a sustainable alternative for marine applications. The findings from the LCA studies reveal that while ammonia-fuelled ships exhibit varying impacts, GWI consistently emerges as the dominant environmental indicator, emphasizing the urgent need to shift from traditional fossil fuels to more sustainable options. Key findings from the study include:

1. Brown ammonia, produced from coal and LNG, demonstrates significant GWI values, highlighting the necessity of reducing reliance on these high-emission fuels. In contrast, blue ammonia, especially when coupled with CCS technologies, and green ammonia, show much lower GWI values, positioning them as promising solutions to reduce the maritime sector's environmental impact.
2. The evaluation of desktop ship designs shows that variations in storage tank designs—such as size, weight, and material choices—can affect emission profiles. However, GWI remains the primary environmental concern, indicating that while improvements in tank configurations can enhance environmental performance, the urgent need to transition to cleaner fuels should remain a priority.
3. The sensitivity analysis further highlights the environmental impact differences among fuel types, particularly pointing to the higher emissions associated with HFO and MDO in comparison to ammonia. The significantly lower acidification and eutrophication impacts of ammonia-based fuels suggest their ability to mitigate common environmental issues related to traditional marine fuels.

Based on these findings, the following recommendations are proposed:

1. Prioritize the development and adoption of green ammonia as the primary fuel source for maritime applications, due to its low GWI and minimal environmental impact. Investments in renewable energy for hydrogen production should be accelerated to ensure a sustainable ammonia supply chain.
2. Support policies and regulations that encourage the transition to ammonia fuels, such as financial incentives for green and blue ammonia technologies, and stricter emission standards for conventional fossil fuels.
3. Promote the integration of CCS technologies with blue ammonia production to further reduce GWI and improve the environmental feasibility of ammonia as a marine fuel.
4. Focus on designing advanced storage tank configurations that reduce weight and maximize efficiency without compromising safety. Emphasis should be placed on using sustainable materials to lower the environmental impact associated with tank production and operation.
5. Continue conducting long-term studies on the environmental impacts of ammonia fuels, including potential ecosystem effects and operational challenges in different maritime settings. These studies should assess the entire lifecycle of ammonia production, storage, and use to identify further opportunities for improvement.

By implementing these recommendations, the maritime industry can significantly reduce its environmental impact and contribute to global sustainability objectives, facilitating the transition toward a more resilient and eco-friendly future for shipping.

The LCA study is dependent on data collection from both literature and the project, and then the following limitations and assumptions are considered:

1. The data collected from the literature and the project may not fully capture the LCA's performance, making sensitivity and uncertainty analysis essential to assessing the impact of parameter variation and the data's confidence level.
2. The SHIPLCA software is used according to the guidance and manual. It has been verified and validated within the SHIPLYS project.
3. Operational profiles and annual fuel consumption are theoretically derived from collaborative partners in the NH3CRAFT project. However, the LCA results may differ with real operational data.
4. Due to the unavailability of maintenance data for the containment system, the maintenance phase has been excluded from the study.
5. Several environmental impact data are gathered from literature and applied to this LCA study directly. It will affect the composition of the LCI; however, the LCIA result will not be affected by using these published data from literature.

Table 28
Definition of data confidence levels.

Evidence Type	Confidence Level		
	Strong	Medium	Weak
Judgments supported by experts	Over 75%	25% ~ 75%	Less than 25%
Assumptions agreed by experts	Over 75%	25% ~ 75%	Less than 25%

Table 29
Summary of data confidence study.

Item number	Data description	Data sources	Level of confidence
1	Ammonia production energy and emission	Literature	73.75
2	Ammonia transportation energy and emission	Database, Literature	73.75
3	Ammonia storage energy and emission	Literature	73.75
4	Ammonia bunkering energy and emission	Literature	73.75
5	Ammonia tank to wake emission (utilisation on ships)	Literature	78.75
6	Ship particulars of the demonstrator and desktop study ships	Project	92.50
7	Annual main engine fuel oil consumption	Project	91.25
8	Annual auxiliary engine fuel oil consumption	Project	91.25
9	Size and weight of the fuel containment system	Project, assumption	93.25
10	Production emission of steel and glass fiber tanks	Assumption, Database, Literature	82.00
11	Shipyards construction machinery specification	Database	77.00
12	Tank construction, installation and dismantling working hours	Assumption	69.50
13	Electricity production emissions	Database	80.00

CRedit authorship contribution statement

Haibin Wang: Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Peilin Zhou:** Supervision, Funding acquisition. **Byongug Jeong:** Supervision, Funding acquisition. **Ana Mesbahi:** Writing – original draft, Project administration, Data curation. **M.P. Mujeeb-Ahmed:** Writing – original draft, Investigation, Data curation. **Hayoung Jang:** Writing – original draft, Methodology. **Alexandros Giannakis:** Data curation. **Konstantinos Sykaras:** Data curation. **Astrinos Papadakis:** Data curation.

Declaration of competing interest

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

Acknowledgements

The work presented in this paper has been carried out within the UKRI HORIZON-CL5-2021-D5-01 NH₃CRAFT project, co-funded by the European Commission (Project Number: 101056831 (HE), 10105683 (IUK)). The authors would like to express sincere gratitude to all the partners in the project including designers, Class Societies, industries, and academia for their critical review and constructive feedback during the course of this study. The views and opinions presented in this paper are those of the authors alone.

Data availability

Data will be made available on request.

References

- Ahmed, S., Li, T., Li, S.Y., Chen, R., 2023. Comparative life cycle impact assessment of offshore support vessels powered by alternative fuels for sustainable offshore wind operations using machine learning. *J. Ocean Eng. Sci.* <https://doi.org/10.1016/j.joes.2023.10.005>.
- Al-Breiki, M., Bicer, Y., 2020. Technical assessment of liquefied natural gas, ammonia and methanol for overseas energy transport based on energy and exergy analyses. *Int. J. Hydrogen Energy* 45, 34927–34937. <https://doi.org/10.1016/j.ijhydene.2020.04.181>.
- Al-Enazi, A., Okonkwo, E.C., Bicer, Y., Al-Ansari, T., 2021. A review of cleaner alternative fuels for maritime transportation. *Energy Rep.* 7, 1962–1985. <https://doi.org/10.1016/j.egy.2021.03.036>.
- Ampah, J.D., Yusuf, A.A., Afrane, S., Jin, C., Liu, H., 2021. Reviewing two decades of cleaner alternative marine fuels: towards IMO's decarbonization of the maritime transport sector. *J. Clean. Prod.* 320, 128871. <https://doi.org/10.1016/j.jclepro.2021.128871>.
- Arabnejad, M.H., Thies, F., Yao, H.D., Ringsberg, J.W., 2024. Zero-emission propulsion system featuring, flettner rotors, batteries and fuel cells, for a merchant ship. *Ocean Eng.* 310, 118618. <https://doi.org/10.1016/j.oceaneng.2024.118618>.
- Bañares-Alcántara, R., Dericks, G., Fiaschetti, M., Grünwald, P., Masa Lopez, J., Tsang, E., Yang, A., Ye, L., Zhao, S., 2015. Analysis of Islanded NH₃-based Energy Storage Systems Analysis of Islanded Ammonia-based Energy Storage Systems.
- Bicer, Y., Dincer, I., 2018. Environmental impact categories of hydrogen and ammonia driven transoceanic maritime vehicles: a comparative evaluation. *Int. J. Hydrogen Energy* 43, 4583–4596. <https://doi.org/10.1016/j.ijhydene.2017.07.110>.
- Burchart-Korol, D., 2013. Life cycle assessment of steel production in Poland: a case study. *J. Clean. Prod.* 54, 235–243. <https://doi.org/10.1016/j.jclepro.2013.04.031>.
- Chalaris, I., Jeong, B., Jang, H., 2022. Application of parametric trend life cycle assessment for investigating the carbon footprint of ammonia as marine fuel. *Int. J. Life Cycle Assess.* 27, 1145–1163. <https://doi.org/10.1007/S11367-022-02091-4/FIGURES/9>.
- CML - Department of Industrial Ecology, 2016. CML-IA Characterisation Factors [WWW Document].
- Dong, D.T., Schönborn, A., Christodoulou, A., Ölcer, A.I., González-Celis, J., 2024. Life cycle assessment of ammonia/hydrogen-driven marine propulsion. *Proc. IME M J. Eng. Marit. Environ.* 238, 531–542. https://doi.org/10.1177/14750902231207159/ASSET/7987B65C-9533-495E-8877-FD215C9F7B9D/ASSETS/IMAGES/LARGE/10.1177_14750902231207159-FIG10.JPG.

- Ejder, E., Arslanoglu, Y., 2022. Evaluation of ammonia fueled engine for a bulk carrier in marine decarbonization pathways. *J. Clean. Prod.* 379, 134688. <https://doi.org/10.1016/j.jclepro.2022.134688>.
- Goerlandt, F., Reniers, G., 2016. On the assessment of uncertainty in risk diagrams. *Saf. Sci.* 84, 67–77. <https://doi.org/10.1016/J.SSCI.2015.12.001>.
- Harahap, F., Nurdawati, A., Conti, D., Leduc, S., Urban, F., 2023. Renewable marine fuel production for decarbonised maritime shipping: pathways, policy measures and transition dynamics. *J. Clean. Prod.* 415, 137906. <https://doi.org/10.1016/j.jclepro.2023.137906>.
- Hörteborn, A., Hassellöv, I.-M., 2023. Economic incentives and technological limitations govern environmental impact of LNG feeder vessels. *J. Clean. Prod.* 429, 139461. <https://doi.org/10.1016/j.jclepro.2023.139461>.
- Huib, H.P., Van, Essen, Croezen, H., Nielsen, J., 2003. Environmental Analysis of Ethylene and Propylene Transport Within the EU.
- Huijbregts, M.A.J., 2016. Recipe 2016 A Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level Report I: Characterization.
- IMO, 2024. IMO CCC 10: Interim Guidelines for Ammonia and Hydrogen as Fuel [WWW Document]. URL: <https://www.dnv.com/news/imo-ccc-10-interim-guidelines-for-ammonia-and-hydrogen-as-fuel/>.
- Inal, O.B., Zincir, B., Deniz, C., 2022. Investigation on the decarbonization of shipping: an approach to hydrogen and ammonia. *Int. J. Hydrogen Energy* 47, 19888–19900. <https://doi.org/10.1016/j.ijhydene.2022.01.189>.
- Islam Rony, Z., Mofijur, M., Hasan, M.M., Rasul, M.G., Jahirul, M.I., Forruque Ahmed, S., Kalam, M.A., Anjum Badruddin, I., Yunus Khan, T.M., Show, P.-L., 2023. Alternative fuels to reduce greenhouse gas emissions from marine transport and promote UN sustainable development goals. *Fuel* 338, 127220. <https://doi.org/10.1016/j.fuel.2022.127220>.
- ISO, 2006a. ISO 14040:2006 - Environmental Management – Life Cycle Assessment – Principles and Framework [WWW Document].
- ISO, 2006b. ISO 14044:2006 - Environmental Management — Life Cycle Assessment — Requirements and Guidelines [WWW Document].
- Jang, H., Jeong, B., Zhou, P., Ha, S., Park, C., Nam, D., Rashedi, A., 2022. Parametric trend life cycle assessment for hydrogen fuel cell towards cleaner shipping. *J. Clean. Prod.* 372, 133777. <https://doi.org/10.1016/j.jclepro.2022.133777>.
- Karvounis, P., Theotokatos, G., Boulougouris, E., 2024. Environmental-economic sustainability of hydrogen and ammonia fuels for short sea shipping operations. *Int. J. Hydrogen Energy* 57, 1070–1080. <https://doi.org/10.1016/j.ijhydene.2024.01.058>.
- Kourkoumpas, D.-S., Bon, A., Sagani, A., Atsonios, K., Grammelis, P., Karellas, S., Kakaras, E., 2024. Life cycle assessment of novel thermochemical – biochemical biomass-to-liquid pathways for sustainable aviation and maritime fuel production. *Bioresour. Technol.* 393, 130115. <https://doi.org/10.1016/j.biortech.2023.130115>. Leeds City Gate, 2016. Leeds City Gate.
- Liu, L., Wu, J., Liu, H., Wu, Y., Wang, Y., 2024. Investigation of combustion and emissions characteristics in a low-speed marine engine using ammonia under thermal and reactive atmospheres. *Int. J. Hydrogen Energy* 63, 1237–1247. <https://doi.org/10.1016/j.ijhydene.2024.02.308>.
- Lu, M., Long, W., Wei, F., Dong, D., Cong, L., Dong, P., Tian, H., Chen, X., Chen, S., Wang, Y., Wang, P., 2024. Assessment of carbon-free fuel ammonia combustion with low methanol blends in reducing GHG emissions including N₂O. *J. Clean. Prod.* 463, 142755. <https://doi.org/10.1016/j.jclepro.2024.142755>.
- Machaj, K., Kupecki, J., Malecha, Z., Morawski, A.W., Skrzypkiewicz, M., Stanclik, M., Chorowski, M., 2022. Ammonia as a potential marine fuel: a review. *Energy Strategy Rev.* 44, 100926. <https://doi.org/10.1016/j.esr.2022.100926>.
- Mandegari, M., Ebadian, M., Saddler, J. John, 2023. The need for effective life cycle assessment (LCA) to enhance the effectiveness of policies such as low carbon fuel standards (LCFS's). *Energy Policy* 181, 113723. <https://doi.org/10.1016/j.enpol.2023.113723>.
- Mckenney, T., 2023. Managing Emissions from ammonia-fueled Vessels.
- Micoli, L., Russo, R., Coppola, T., 2024. Advancing zero-emission maritime solutions: case study of an ammonia-powered fuel cell system implementation. *Energy Convers. Manag.* X 22, 100588. <https://doi.org/10.1016/j.ecmx.2024.100588>.
- NH3CRAFT, 2024. NH 3 CRAFT-SAFE AND EFFICIENT STORAGE OF AMMONIA WITHIN SHIPS SPECIFICATION OF DESKTOP STUDIES.
- NH3CRAFT, 2022. Safe and efficient storage of ammonia within ships | NH3CRAFT | project | fact sheet | HORIZON | CORDIS | european commission [WWW Document]. URL: <https://cordis.europa.eu/project/id/101056831>.
- Perčić, M., Vladimir, N., Fan, A., 2020. Life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-sea shipping: a case study of Croatia. *Appl. Energy* 279, 115848. <https://doi.org/10.1016/j.apenergy.2020.115848>.
- PwC, 2023. Life Cycle Assessment of CFGF-Continuous Filament Glass Fibre Products PwC-Sustainable Performance and Strategy 63 Rue De Villiers F-92208 Neuilly-sur-Seine Cedex.
- Royal Society, 2020. Ammonia: Zero-Carbon Fertiliser, Fuel and Energy Store POLICY BRIEFING.
- Sánchez, A., Martín Rengel, M.A., Martín, M., 2023. A zero CO₂ emissions large ship fuelled by an ammonia-hydrogen blend: reaching the decarbonisation goals. *Energy Convers. Manag.* 293, 117497. <https://doi.org/10.1016/j.enconman.2023.117497>.
- Schuller, O., Bopp, J., Rapp, J., 2024. 1 St Life Cycle GHG Emission Study on the Use of Ammonia as Marine Fuel Report Version: V1.1.
- Tomos, B.A.D., Stamford, L., Welfle, A., Larkin, A., 2024. Decarbonising international shipping – a life cycle perspective on alternative fuel options. *Energy Convers. Manag.* 299, 117848. <https://doi.org/10.1016/j.enconman.2023.117848>.
- Ursúa, A., Gandía, L.M., Sanchis, P., 2012. Hydrogen production from water electrolysis: current status and future trends. In: <https://doi.org/10.1109/JPROC.2011.2156750>.
- Wang, H., Zhou, P., Liang, Y., Jeong, B., Mesbahi, A., 2020. Optimization of tugboat propulsion system configurations: a holistic life cycle assessment case study. *J. Clean. Prod.* 259, 120903. <https://doi.org/10.1016/J.JCLEPRO.2020.120903>.
- Wang, Z., Dong, B., Yin, J., Li, M., Ji, Y., Han, F., 2024. Towards a marine green power system architecture: integrating hydrogen and ammonia as zero-carbon fuels for sustainable shipping. *Int. J. Hydrogen Energy* 50, 1069–1087. <https://doi.org/10.1016/j.ijhydene.2023.10.207>.
- Wei, W., Li, G., Zhang, H., Wei, F., Cai, W., Dong, D., Zhang, Z., 2024. NO generation in marine dual-fuel engines: effects of ammonia blending ratio and spark ignition timing. *J. Clean. Prod.* 470, 143332. <https://doi.org/10.1016/j.jclepro.2024.143332>.
- Wu, S., Miao, B., Chan, S.H., 2022. Feasibility assessment of a container ship applying ammonia cracker-integrated solid oxide fuel cell technology. *Int. J. Hydrogen Energy* 47, 27166–27176. <https://doi.org/10.1016/j.ijhydene.2022.06.068>.
- Wu, Y., Chen, A., Xiao, H., Jano-Ito, M., Alnaeli, M., Alnajideen, M., Mashruk, S., Valera-Medina, A., 2023. Emission reduction and cost-benefit analysis of the use of ammonia and green hydrogen as fuel for marine applications. *Green Energy Res.* 1, 100046. <https://doi.org/10.1016/j.gerr.2023.100046>.
- Zincir, B., 2022. Environmental and economic evaluation of ammonia as a fuel for short-sea shipping: a case study. *Int. J. Hydrogen Energy* 47, 18148–18168. <https://doi.org/10.1016/j.ijhydene.2022.03.281>.
- Zincir, B.A., Arslanoglu, Y., 2024. Comparative life cycle assessment of alternative marine fuels. *Fuel* 358, 129995. <https://doi.org/10.1016/j.fuel.2023.129995>.
- Zobaa, A.F., Rusu, E., Kolodziejcki, M., Michalska-Pozoga, I., 2023. Battery energy storage systems in ships' hybrid/electric propulsion systems. *Energies* 16, 1122. <https://doi.org/10.3390/EN16031122>, 2023, Vol. 16, Page 1122.