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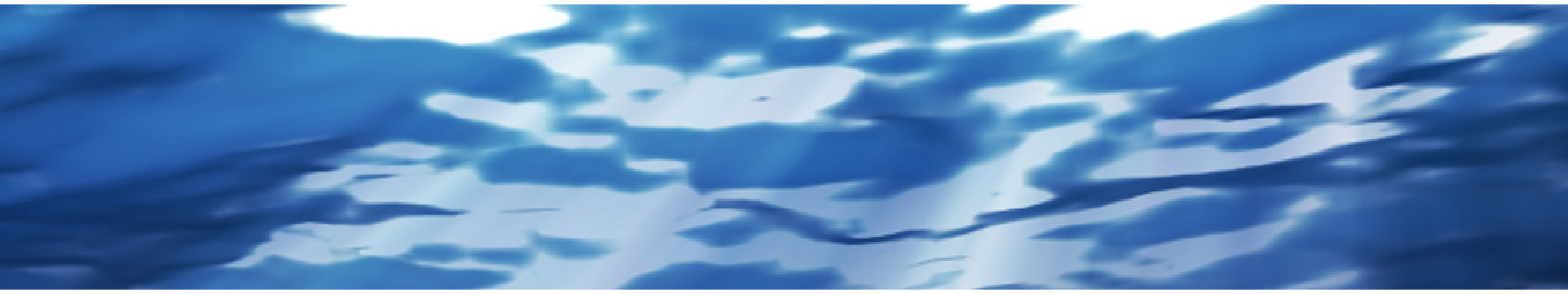
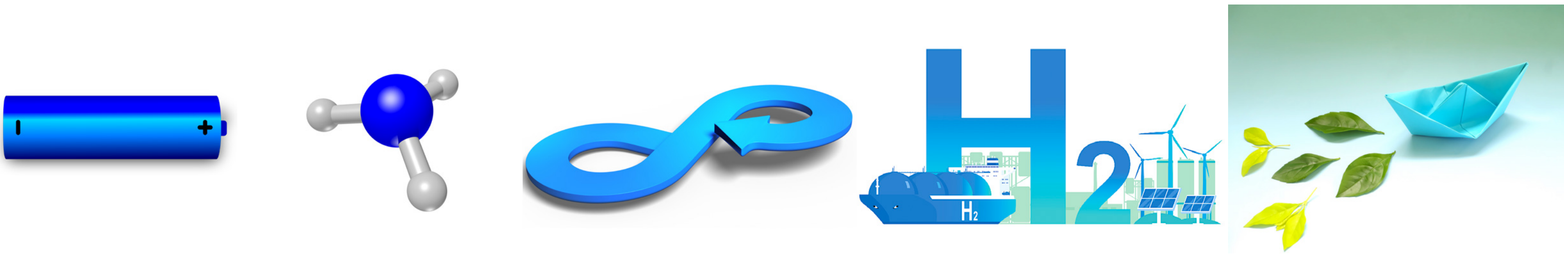


LIGHTHOUSE REPORTS

Hydrogen, ammonia, and battery-electric propulsion for future shipping



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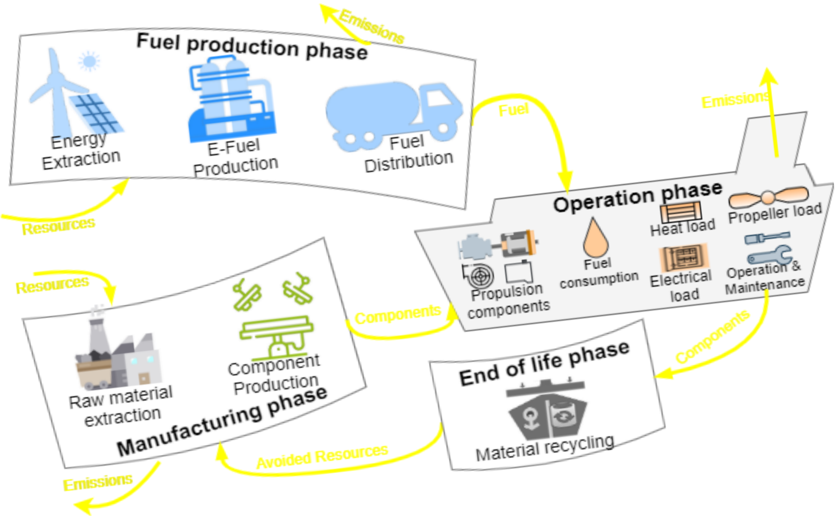
HÅLLBAR
SJÖFART



Hydrogen, ammonia, and battery-electric propulsion for future shipping

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A research project carried out within the Swedish Transport Administration's industry program Sustainable Shipping, operated by Lighthouse

Summary

For a shift towards decarbonization of the shipping sector, it is important to switch to alternative fuels for ships. Recently, interest is gaining in hydrogen, ammonia, and battery-electric as these can enable zero-carbon emissions during ship operation. The project aims to deepen the life cycle knowledge on the environmental and economic sustainability of decarbonization pathways based on hydrogen, ammonia, and direct electrification and related propulsion system for ships. The life cycle knowledge based on system thinking obtained in this project will benefit actors that are involved in the complex task of choosing or regulating marine fuels and propulsion technologies.

In this project, three ships that operate in different ways—a service vessel, a tanker, and a RoPax ferry—are studied and assessed in terms of safety on board, feasibility, environmental impacts over the whole life cycle, and economic factors over the whole supply chain. The use of fuel cells and engines as energy converters onboard for hydrogen and ammonia is considered. Conceptual designs for the first two case study ships are also developed as part of the project. Safety assessment is performed by organizing an online workshop including different stakeholders within the shipping sector. An integrated life cycle assessment method developed during the project is used for environmental assessment and cost assessment of the pathways for better understanding of balance between cost and environmental impact.

The result of the project shows that the technical feasibility of the different fuels varies with the ship type. The volumetric and gravimetric energy density of the fuel, as well as the amount of energy needed between bunkering, are the most important factors affecting technical feasibility. The type of safety concerns also differs between the fuel choice and also between ship types with the highest safety risk for the RoPax ship related to the exposure of ammonia to the passengers.

This project shows that it is possible to substantially reduce greenhouse gas (GHG) emissions over life cycle by introducing ammonia, hydrogen, and battery-electric propulsion. However, even if these fuels are free from carbon atoms, ship operations are not necessarily free from carbon-related emissions as pilot fuels that could contain carbon is needed for some propulsion system. Reduced climate impact is indicated to come at the expense of several other impact categories, such as human toxicity, water use, and resource use (minerals and metals), and in addition, while using ammonia the risk of eutrophication is high.

For the same type of fuel, fuel cells have greater impact reduction potential than engine options; however, engines are more cost competitive. The climate reduction potential and cost of the fuels are closely related to the carbon intensity and price of electricity respectively. This study's estimate of the carbon abatement cost indicate that policies might need to penalize GHG emission with at least 250–300 €/tCO_2eq.

Sammanfattning

För att minska sjöfartens utsläpp av växthusgaser är övergången till alternativa bränslen viktig. På senare tid har intresset ökat för vätgas, ammoniak och batterielektrisk framdrift eftersom dessa kan möjliggöra noll koldioxidutsläpp under fartygets drift. Projektet syftar till att fördjupa livscykelkunskapen om den miljömässiga och ekonomiska hållbarheten för olika sätt att minska växthusgasutsläppen baserade på vätgas, ammoniak och direkt elektrifiering och tillhörande framdrivningssystem för fartyg. Kunskapen från livscykelanalyserna i detta projekt kommer kunna vara till nytta för aktörer som är involverade i den komplexa uppgiften att välja eller reglera marina bränslen och framdrivningstekniker.

I detta projekt studeras och bedöms tre fartyg med olika punktion och operation – ett servicefartyg, ett tankfartyg och en RoPax-färja – med avseende på säkerhet ombord, genomförbarhet, miljöpåverkan över hela livscykeln och ekonomiska faktorer över hela leveranskedjan. Användningen av bränsleceller och motorer för energiomvandling ombord för vätgas och ammoniak övervägs. Konceptuella utformningar för de två första fallstudiefartygen utvecklas också. Säkerhetsbedömningen görs genom en online-workshop med olika intressenter inom sjöfartssektorn. En integrerad livscykelanalysmetod som utvecklats under projektet används för miljöbedömning och kostnadsbedömning av de studerade alternativen för bättre förståelse av balansen mellan kostnad och miljöpåverkan.

Resultatet av projektet visar att den tekniska genomförbarheten för de olika bränslena varierar med fartygstypen. Bränslets volymetriska och gravimetriska energitäthet, liksom mängden energi som behövs mellan bunkring är de viktigaste faktorerna som påverkar den tekniska genomförbarheten. Typen av säkerhetsproblem skiljer sig också mellan bränslena och även mellan fartygstyperna med de högsta säkerhetsriskerna för RoPax-fartyget relaterade till exponeringen av ammoniak för passagerarna.

Projektet visar att det är möjligt att avsevärt minska utsläppen av växthusgaser över livscykeln genom att introducera ammoniak, vätgas och batteri-elektrisk framdrift. Även om dessa bränslen är fria från kolatomer, är fartygsdriften dock inte nödvändigtvis fri från koldioxidutsläpp eftersom pilotbränslen som kan innehålla kol behövs för vissa framdrivningssystem. Minskad klimatpåverkan indikeras ske på bekostnad av flera andra miljöpåverkanskategorier, såsom mänsklig toxicitet, vattenanvändning och resursanvändning (mineraler och metaller), och dessutom är risken för övergödning hög vid användning av ammoniak.

För samma typ av bränsle har bränsleceller större potential att minska miljöpåverkan än förbränningsmotoralternativ; motorer är dock mer konkurrenskraftiga ur ett kostnadsperspektiv. Drivmedlens växthusgasreduktionspotential och kostnad är nära kopplade till kolintensiteten respektive elpriset. Denna studies uppskattning av kostnaden för att minska koldioxidutsläppen tyder på att styrmedel med kostnader för utsläpp av växthusgaser med minst 250–300 €/tCO_2eq kan behövas.

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Abbreviations

BE	Battery electric
CCS	Carbon capture and storage
CO_2	Carbon dioxide
DWT	Deadweight tonnage
FC	Fuel cell
GHG	Greenhouse gas
GT	Gross tonnage
H_2	Hydrogen
HFO	Heavy fuel oil
ICE	Internal combustion engine
IMO	International Maritime Organization
LCA	Life cycle assessment
LCC	Life cycle costing
LNG	Liquefied natural gas
MGO	Marine gas oil
NH_3	Ammonia
NOx	Nitrogen oxides
PEMFC	Proton exchange membrane
PM	Particulate matter
PSM	Power System Mass
PSV	Power System Volume
SOx	Sulphur oxides
SOFC	Solid oxide fuel cell
2SICE	2-stroke engines
4SICE	4-stroke engines
TRL	Technology readiness level

1 Introduction

Ships transport over 90% of global trade and this is expected to rise by 57–126 % compared to 2018 based on different projections from The International Maritime Organization (IMO) [1]. Currently, most ships use highly polluting fossil fuels like heavy fuel oil (HFO) and marine gas oil (MGO), which results in emissions equal to about 3% of total global anthropogenic carbon dioxide (CO_2) emissions [1]. In addition, emissions of nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter (PM), and hydrocarbons from ships have a negative impact on human health and the natural environment, see Andersson et al. [2]. As the industry is growing, and vessels constructed in the next few years will remain in service until 2050 and beyond, this is a pressing matter.

The IMO has adopted a revised strategy to reduce greenhouse gas (GHG) emissions from shipping, including indicative checkpoints of 20% reduction in emissions by 2030, a 70% reduction by 2040 (compared to 2008 levels), and the goal of achieving net-zero emissions by 2050 [3]. The European Union (EU) is finalizing the Fuel EU Maritime regulation as part of its Fit for 55 legislative packages [4], with the goal of increasing the use of renewable and low-carbon fuels in the maritime sector and bringing the shipping industry under the EUs emission trading scheme [5]. Sweden has also climate goals which include that transport (including Swedish domestic shipping) should reduce GHG emissions by 70% by 2030 and that Sweden should be net-zero by 2045. It is also suggested that part of the GHG emissions from Swedish international shipping should be included in the national targets [6]. Such drives have led to increased interest from both industry, authorities, and politicians to learn more about the different alternative marine fuels and propulsion options having a potential to reduce climate impact from shipping.

GHG emissions are not limited to the ship operation but are also associated with other parts of the life cycles of ships including the production of the fuel, the transport of fuel, the building of fuel infrastructure, and the manufacturing of ship components. For this reason, it is essential to evaluate the fuel and vessel systems from a system perspective considering cradle to grave to comprehend any change from the present situation. A system-level evaluation facilitates the identification of underlying factors that influence the performance of various transition pathways and the operational, functional, and technical characteristics of the vessel.

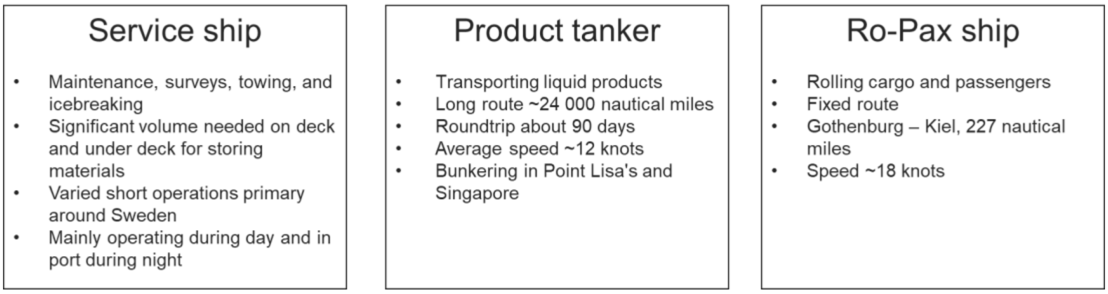
1.1 Aim

The main aim of the project, summarized in this report, is to deepen the life cycle knowledge on the environmental and economic sustainability of alternative fuels and related propulsion systems for ships and thereby provide decision support for actors that are involved in the complex task of choosing or regulating marine fuels and propulsion technologies. Specifically, this project evaluates hydrogen (H_2), ammonia (NH_3), and battery-electric propulsion as potential zero-carbon alternatives because they all contain no carbon atoms. Alternative fuels like methanol and conventional fuels like marine gas oil will also be evaluated alongside these and compared to various types of vessels.

H_2 and NH_3 are new fuels within the maritime domain, and each has safety challenges that need to be addressed.

1.2 Scope and limitation

The scope of the project is fixed on the energy carrier life cycle and the powertrain components life cycle. As mentioned, the energy carriers in focus of this project are H_2, NH_3, and electricity (battery electric) and in addition methanol is also included. The use of alternative fuels both in fuel cells and internal combustion engines will be evaluated. The battery-electric, fuel cells and combustion engines work with different principles and the onboard configurations of components are also different. The configurations also vary with vessel types depending on their function and operation for example the use of 2-stroke engines and 4-stroke engines. The project is based on three case study vessels (a service ship, a product tanker, and a Ro-Pax ship) having different operation profiles and performing different functions, see Figure 1.



Service ship

- Maintenance, surveys, towing, and icebreaking
- Significant volume needed on deck and under deck for storing materials
- Varied short operations primary around Sweden
- Mainly operating during day and in port during night

Product tanker

- Transporting liquid products
- Long route ~24 000 nautical miles
- Roundtrip about 90 days
- Average speed ~12 knots
- Bunkering in Point Lisa's and Singapore

Ro-Pax ship

- Rolling cargo and passengers
- Fixed route
- Gothenburg – Kiel, 227 nautical miles
- Speed ~18 knots

Figure 1: The three case study ships assessed in the project "Hydrogen, ammonia and battery-electric propulsion for future shipping".

The combination of each energy carrier and powertrain are considered as possible shipping decarbonization pathways and together act as a technological system comprising various processes, technologies, and interactions. Since many technologies/processes within this technological system are at early stages of development, the technological system itself can be considered as emerging. Also, the technological system is specific for each ship type.

The fuel pathways included in the scope of the report are as shown in Figure 2. A life cycle perspective is used in this report both when assessing environmental impacts and costs. This for examples includes those emissions occurring during production of renewable power plants is included.

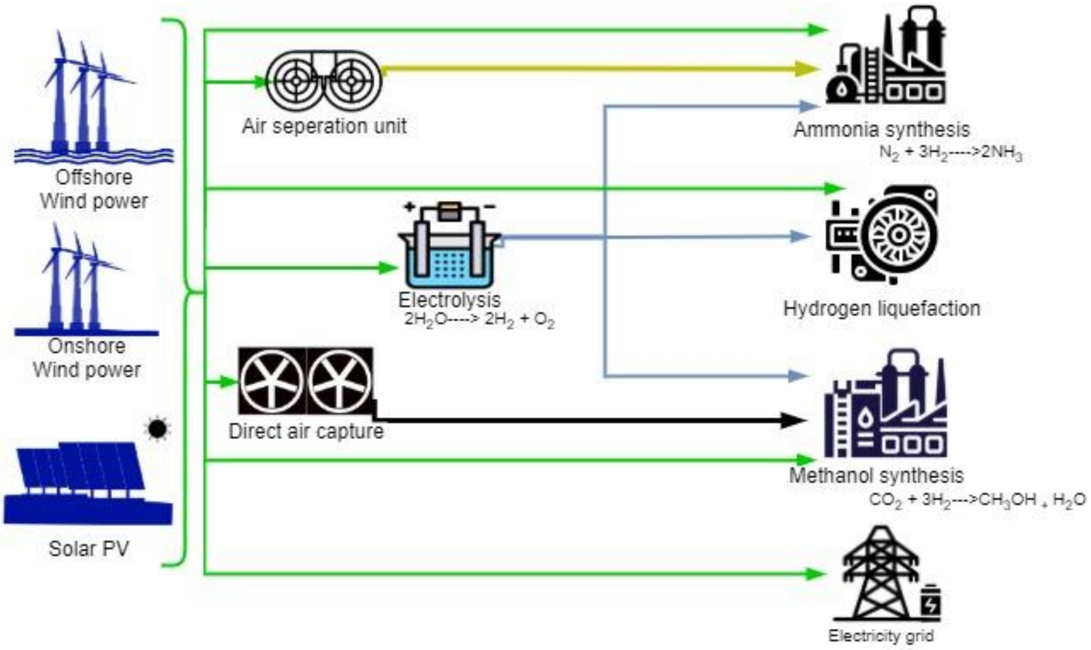


Figure 2: Electro-fuel pathways assessed in this report.

The other part of the technological system is the components onboard ship used for propulsion and other energy demands. These include storage tanks for each energy carrier, energy converters (internal combustion engine (ICE) or fuel cell (FC)),), drive technology (electric or gear box or direct), and other additional components. In this report, system configurations based on the energy converters 2-stroke ICE (2SICE), 4-stroke ICE (4SICE), proton exchange membrane FC (PEMFC), and solid oxide FC (SOFC), and battery electric (BE) are considered as shown in Figure 3. For 2SICEs, the drive is directly from the engine, whereas there is a gearbox for 4S engines. For FCs and BE the propulsion is with the help of electric motors. For ICEs and SOFC, excess heat is available for the heating load.

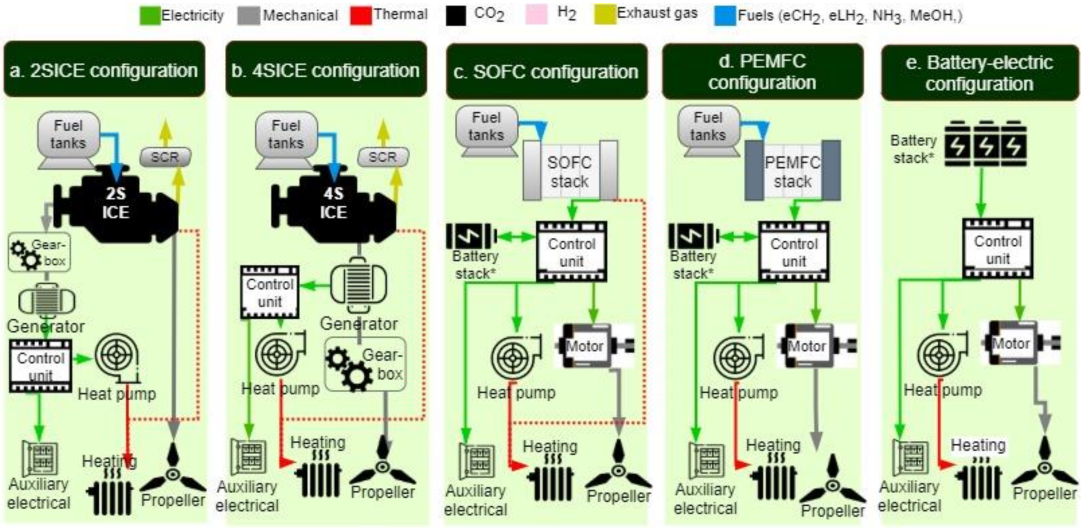


Figure 3: Onboard powertrain configurations covered in this study for different energy carriers.

The project does not consider H_2 or NH_3 produced from biomass pathway e.g., green H_2 from biogas with CCS. Fuels like e-diesel, hydrogenated vegetable oil, dimethyl ether etc. are also not assessed in this study. Energy converters like spark ignition engines and fuel cells other than PEMFC and SOFC are also not evaluated in the study.

1.3 Outline of the report

This report is divided into 5 chapters summarising the main findings of the project called "Hydrogen, ammonia and battery-electric propulsion for future shipping". In Chapter 2, the integrated cost and environmental life cycle framework developed during the project is shortly described. In Chapter 3, the risk and safety considerations and assessments done in the project are described. In Chapter 4, the cost and environmental performance results of compared options are summarised. Finally, in Chapter 5 the results are put into the larger context and some recommendations are discussed.

1.4 Additional publications from this project

As mentioned above this report summarises the main findings of the project "Hydrogen, ammonia and battery-electric propulsion for future shipping". However, the project has also contributed to three scientific articles, two conference proceedings and a licentiate thesis, listed below, where more detailed information can be found.

- Korberg, A., Brynolf, S., Grahn, M., Skrov, I., 2021. Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. Renewable and Sustainable Energy Reviews 142.
- Kanchiralla, F.M., Brynolf, S., Malmgren, E., Hansson, J., Grahn, M., 2022. Life-Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free Shipping. Environ Sci Technol 56, 12517-12531.
- Kanchiralla, F.M., Brynolf, S., Olsson, T., Ellis, J. Hansson, J., Grahn, M., 2023. How do variations in ship operation impact the techno-economic feasibility and the environmental performance of fossil-free fuels? A life cycle study. *Applied Energy 2023 Vol. 350, DOI: 10.1016/j.apenergy.2023.121773*
- Kanchiralla, F.M, 2023. Life cycle navigation through future energy carriers and propulsion options for the energy transition in shipping. Licentiate thesis, Mechanics and Maritime Sciences, Chalmers University of Technology, Gothenburg, Sweden.
- Kanchiralla. F. M., Brynolf. S, Malmgren. E, Grahn. M; 'Life cycle cost comparison of zero-carbon propulsion systems with different fuels for marine applications'; IAME 2021, Rotterdam; November 25 to 27, 2021.
- Kanchiralla, F.M, Brynolf, S 'Integrating life cycle assessment and life cycle costing for evaluating decarbonization pathways in shipping' The 11th International Conference on Life Cycle Management, September 6 to 8, 2023. *Accepted for poster presentation.*

2 An integrated cost and environmental life cycle framework

In order to be able to consistently evaluate the life cycle cost and environmental performance of marine fuels and propulsion technologies, an integrated framework is needed. The framework was developed during the project in steps by adding different methods and approaches for integrated assessment of emerging technological systems. The ISO 14044 [7] guideline is taken as the foundation and identified challenges are mapped to the four phases (goal and scope definition, life cycle inventory, impact assessment, and interpretation), see Table 1.

There are two sets of challenges in the methodology, the first one linked to the assessment of emerging technologies using prospective life cycle assessment (LCA) and the second linked to the integration of life cycle costing (LCC). There are also some common challenges associated with inventory for example data availability and quality (for a more detailed description of the challenges see Kanchiralla [8]).

Table 1: Summary of challenges identified for prospective life cycle assessment and life cycle costing integration that need to be addressed in the methodology.

Challenge	LCA phase
▪ Which functional unit should be used for comparison? ▪ What are the changes associated with technological system change? ▪ Where will the changes influence? ▪ When can technology be assumed to be mature? ▪ What are the changes in other processes associated with the new technological system? ▪ What if multiple emerging technologies are there for the process? e.g: PEMFC, SOFC, alkaline electrolysis cell for electrolysis. ▪ Whether processes associated are also emerging and if yes whether it fits with the time horizon?	**Goal and scope definition**
▪ What would be the parameters of foreground processes once the technology is developed? (Energy, material, and cost inventories) ▪ What would be the temporal changes in the background system?	**Life cycle inventory**
▪ Lack of tool for simultaneous assessment capturing same inventory. ▪ Whether present characterization is relevant over time?	**Impact assessment**
▪ How the uncertainty in the development can be addressed? ▪ If different technology is selected for the foreground process, how would it impact the result?	**Interpretation**

The integrated framework is shown in Figure 4, for a more detailed description see Kanchiralla [8]. The red texts are the challenges identified in Table 3, and the blue boxes are approaches integrated to the framework to address the challenges while performing life cycle analysis.

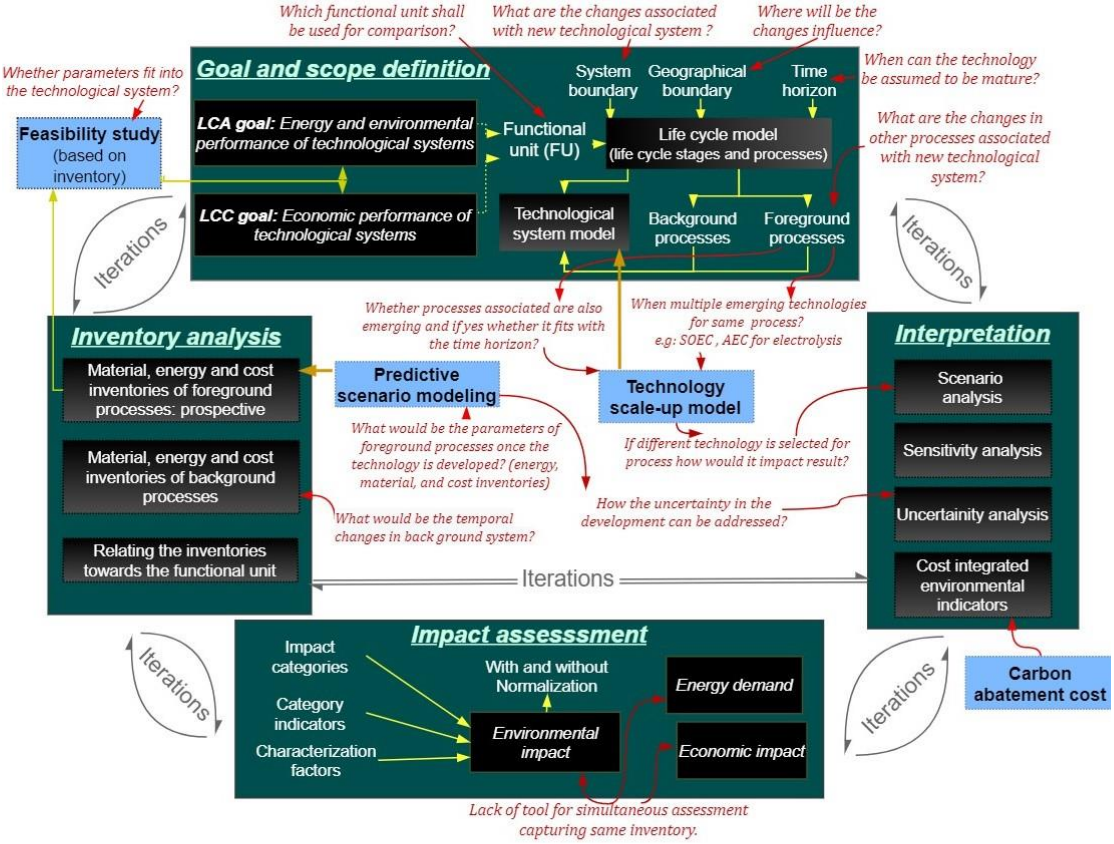
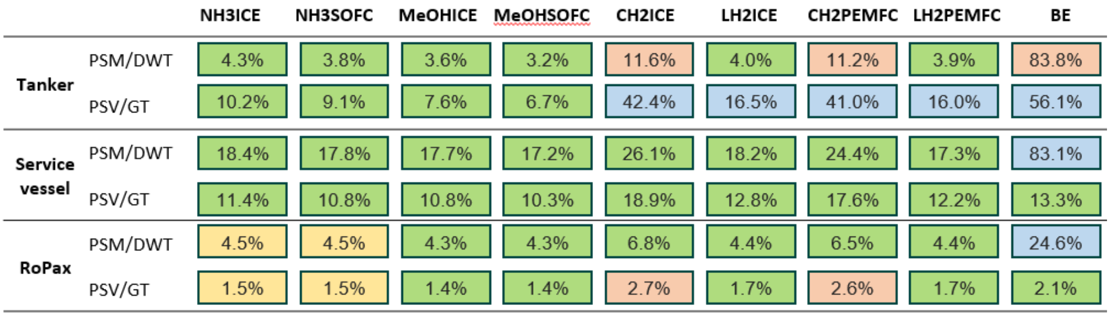


Figure 4: Integrated framework used in this project for the life cycle analysis of alternative fuel in the shipping sector.

2.1 Feasibility study

As part of the integrated framework, the need for a feasibility study was identified. A major feasibility challenge would be lack of storage space on board for new systems that use low-power-density fuels and powertrain technologies. A simplified method is used for feasibility analysis by checking mechanical space available for each vessel, which varies among the different ships by comparing with conventional marine gas oil configuration, the ratio of total powertrain size, including fuel storage, to vessel size is calculated to evaluate feasibility. The mass constraint is evaluated using deadweight tonnage (DWT), while the volume constraint is evaluated using gross tonnage (GT). For mass consideration, the ratio of propulsion components mass (including fuel storage and fuel) to DWT (Power System Mass (PSM)/DWT) is calculated, while the ratio of propulsion machinery volume, Power System Volume (PSV) to GT (PSV/GT) is calculated for volume consideration. If the ratios of decarbonization concepts are greater than three times the mass ratio and two times the volume ratio for the conventional MGO option for each ship type, the design is deemed unfeasible.

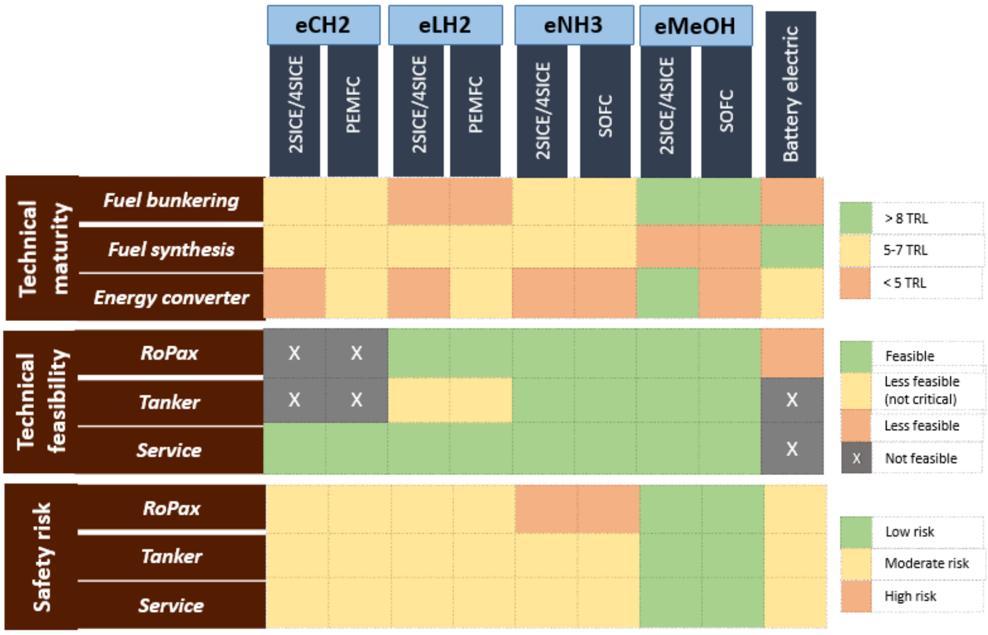
Figure 5 shows the volume and mass feasibility of the various concepts based on the above method. Due to the energy carrier's low energy density and high energy consumption between bunkering, compressed H_2 and battery is impractical for the tanker and the RoPax vessel. The mass constraint is more severe for tankers than for service and RoPax vessels; as a result, the possibility of using the battery option for service and RoPax vessels (shown in blue colour) cannot be ruled out and is therefore subject to further analysis. Similarly, for tanker, volume is not critical, since there is available space on the deck, hence high-volume options cannot be ruled out completely without detail analysis (shown in blue colour).



		NH3ICE	NH3SOFC	MeOHICE	MeOHSOFC	CH2ICE	LH2ICE	CH2PEMFC	LH2PEMFC	BE
Tanker	PSM/DWT	4.3%	3.8%	3.6%	3.2%	11.6%	4.0%	11.2%	3.9%	83.8%
	PSV/GT	10.2%	9.1%	7.6%	6.7%	42.4%	16.5%	41.0%	16.0%	56.1%
Service vessel	PSM/DWT	18.4%	17.8%	17.7%	17.2%	26.1%	18.2%	24.4%	17.3%	83.1%
	PSV/GT	11.4%	10.8%	10.8%	10.3%	18.9%	12.8%	17.6%	12.2%	13.3%
RoPax	PSM/DWT	4.5%	4.5%	4.3%	4.3%	6.8%	4.4%	6.5%	4.4%	24.6%
	PSV/GT	1.5%	1.5%	1.4%	1.4%	2.7%	1.7%	2.6%	1.7%	2.1%

Figure 5: Different ship type concepts' viability. Orange represents a non-feasible option, while green represents a feasible option. Yellow indicates a greater safety risk but is still feasible. Blue indicates infeasibility according to the cut-off criterion; however, the size parameter may not be crucial for the BE option on these ship types.

Other challenges include that the emerging technologies in each technological system need to be matured and that onboard safety need to be guaranteed. The summary of the assessment of technology readiness levels (TRLs), the technical feasibility of the system in vessels, and the risk assessment of safety evaluated shown in Figure 6. It can be noted that these are summarized results where TRL of the least matured emerging technology in the supply chain is only shown (e.g., fuel synthesis category for methanol production includes several emerging technologies including electrolysis, methanol synthesis, and direct air capture).



		eCH2		eLH2		eNH3		eMeOH		
		2SICE/4SICE	PEMFC	2SICE/4SICE	PEMFC	2SICE/4SICE	SOFC	2SICE/4SICE	SOFC	Battery electric
Technical maturity	**Fuel bunkering**	🟨	🟨	🟧	🟧	🟨	🟨	🟩	🟩	🟧
	Fuel synthesis	🟨	🟨	🟨	🟨	🟨	🟨	🟧	🟧	🟩
	Energy converter	🟧	🟨	🟧	🟨	🟧	🟧	🟩	🟧	🟨
Technical feasibility	**RoPax**	X	X	🟩	🟩	🟩	🟩	🟩	🟩	🟧
	Tanker	X	X	🟨	🟨	🟩	🟩	🟩	🟩	X
	Service	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	X
Safety risk	**RoPax**	🟨	🟨	🟨	🟨	🟧	🟧	🟩	🟩	🟨
	Tanker	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟨
	Service	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟨

🟩 > 8 TRL
🟨 5-7 TRL
🟧 < 5 TRL

🟩 Feasible
🟨 Less feasible (not critical)
🟧 Less feasible
X Not feasible

🟩 Low risk
🟨 Moderate risk
🟧 High risk

Figure 6: An overview of the feasibility assessment of the case study ships and investigated technologies.

For the technical feasibility assessment, the mass and volume of different components onboard in each technological system are compared with the reference technological system. The different case study ships have different levels of dimensional constraints, the tanker is more constrained on the mass whereas it is the volume that is critical for the RoPax and the service vessel.

Regarding the safety criteria, the concepts are deemed feasible with additional safety measures, such as gas detection, adaptations to fire detection and suppression, double-walled piping, ventilation in general, determination of safety distances for any venting in the case of H_2, and requirements for ensuring no NH_3 gas release through scrubbing of vent gases. For the protection of the crew in the event of an NH_3 leak, personal protective equipment (including the necessary respiratory protective equipment) should be onboard. Considering the possibility of NH_3 passenger exposure, the risk would be greater for the RoPax. A more detailed description of risk and safety aspects considered for the case study ships in included in Chapter 3.

3 Risk and safety aspects

For the risk and safety aspects considered in this project we focused on evaluating H_2 and NH_3 as they are new fuels within the maritime domain with safety challenges that need to be addressed. Regulations for the use of these fuels on board vessels are currently under development by the IMO [9] and classification societies are also in the process of developing and refining rules. To ensure that the high-level concept designs for the case vessels considered the main hazards, draft regulations and rules were consulted and relevant risk mitigation measures used for other gaseous low flashpoint fuels such as LNG were considered. For the service vessel case, a workshop on design concepts and safety considerations was carried out. Risk and safety aspects with the use of H_2 and NH_3 fuel and the service vessel case study safety workshop are described in the following sub-sections.

3.1 Properties and hazards

Selected properties of anhydrous NH_3 and H_2 are shown in

Table 2. Properties of LNG, which has been used for several year as a marine fuel and is gaseous at ambient temperature and pressure like NH_3 and H_2, are provided for comparison.

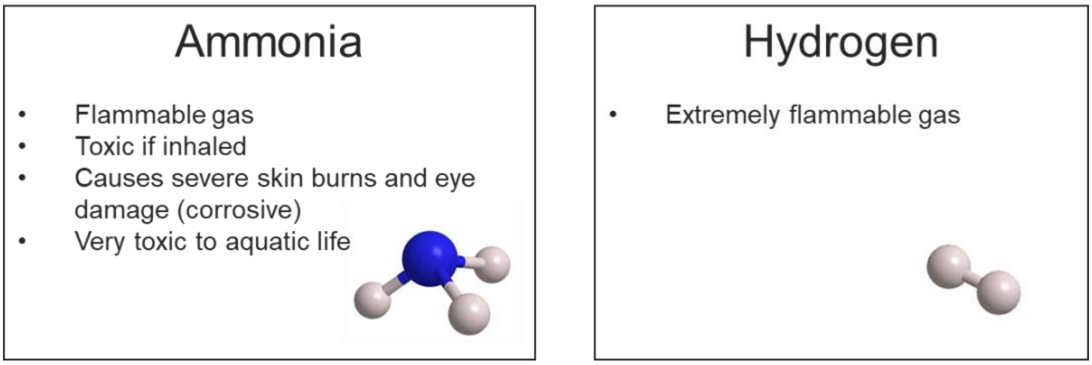
Table 2 Selected properties of NH_3, H_2, and LNG.

Properties	**Ammonia (NH_3)**	**Hydrogen (H_2)**	**LNG**
Boiling temperature at 1 bar (°C)	-33	-253	-162
Liquid density at boiling temp. (kg/m^3)	682	70.5	422 – 450
Flammability Limits (volume % in air)	15 – 33.6	4 – 75	4.5 – 16.5
Minimum ignition energy (mJ)	8	0.019	0.28
Auto ignition temperature (°C)	630	560	530
Specific gravity relative to air (air = 1)	0.60	0.07	0.60
Molecular mass (g/mol)	17	2	16

Data sources: International Programme on Chemical Safety (IPCS) INCEM for ammonia [10] and hydrogen properties [11], except liquid density at boiling temp and minimum ignition energy. Liquid density at boiling temperature for NH_3 and hydrogen from Air Liquide [12]. Ignition energy for NH_3 from DNV GL and Norwegian Maritime Authority [13]. Minimum ignition energy for hydrogen from Kumamoto et al. [14]. LNG properties from Vandebroek and Berghmans [15].

NH_3, H_2, and methane gas (LNG) have a lower specific gravity than air at ambient temperature so will rise when released and have warmed to gaseous form if liquefied. H_2 has a very low ignition energy and wide flammability limits, thus presents a significant risk for fire and explosion if released.

Hazard statements for NH_3 and H_2 according to the harmonised classification and labelling (CLP00) approved by the European Union are shown in Figure 7.



Ammonia

- Flammable gas
- Toxic if inhaled
- Causes severe skin burns and eye damage (corrosive)
- Very toxic to aquatic life

Hydrogen

- Extremely flammable gas

Figure 7:7 Hazard statements for NH_3, anhydrous and H_2 according to the harmonised classification and labelling (CLP00) approved by the European Union [16].

In addition, H_2 in liquid form has cryogenic hazards. H_2 burns with an invisible flame and could, in confined spaces, displace oxygen and cause suffocation.

3.2 Regulations and guidelines

Available interim guidelines and guidance documents for use of NH_3 and H_2 as marine fuels were considered when developing the case study designs. International

Maritime Organization regulations relevant for NH_3 and H_2 use on vessels are as follows:

- IGF Code: The IMO International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF Code) was developed to facilitate the use of these fuels by vessels that are not carrying the substances as cargo. Currently the IGF code has specific design requirements for LNG. Interim guidelines for the use of methyl/ethyl alcohol as fuel were approved by the IMO's MSC in 2020. Draft interim guidelines for ships using H_2 as fuel were agreed at the IMO's Sub-Committee on Carriage of Cargoes and Containers (CCC7). Work is underway to develop guidelines for the safety of ships using NH_3 as fuel, with initial work on collection of safety information reported in 2022 by Japan [17].
- IGC Code: The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk covers transport of gases such as NH_3 in bulk and can be consulted as guidance on storage provisions, transfer, personal protective equipment requirements, etc. until fuel regulations are in place. Currently the code does not permit the use of toxic cargoes as fuel, but amendments are being considered for NH_3. The IGC code currently does not cover liquid H_2 but "Interim Recommendations for Carriage of Liquified Hydrogen in Bulk" were adopted by the IMO in 2016 (Resolution MSC.420(97) and are being further developed.

For vessels using fuel cells, the following interim guidelines should also be consulted as guidance:

- "Draft interim guidelines for the safety of ships using fuel cell power installations", which were approved by the IMO's Maritime Safety Committee (MSC) in April 2022. The document provides criteria for the arrangement and installation of fuel cell power installations, with the aim to have safety and reliability at least equivalent to conventional power systems. Use of gases or low flashpoint fuels in the fuel cells must follow applicable regulations such as the IGF code, as described previously.

Several ship classification societies have published rules, handbooks, and guidelines for NH_3-fuelled vessels including the following examples:

- DNV published class rules for NH_3 as fuel. These entered into force January 1st 2022 (Pt.6 Ch.2 Sec.14).
- ABS has published a guide for ammonia-fuelled vessels (ABS, 2021a).
- Lloyd's Register Maritime Decarbonisation Hub and the Maersk Mc-Kinney Moller Center for Zero Carbon Shipping published recommendations for design and operation of ammonia-fuelled vessels (Lloyd's Register and MMMCZCS, 2023).

Examples of handbooks and guidelines produced for H_2-fuelled vessels by classification societies include:

- Handbook for hydrogen-fuelled vessels, produced by a DNV-led consortium [18].
- White paper on hydrogen as marine fuel, published by ABS [19]

3.3 Workshop on design concepts and safety considerations for the service vessel case study

A workshop was held to identify high-level hazards of the service vessel case study. A structured group review was carried out in a half-day TEAMs workshop held on 5th October 2022. Participants included representatives from the vessel operator, a low flashpoint fuel safety expert from the Swedish flag state, an expert in gas safety, an engine manufacturer, an NH_3 safety expert, naval architects familiar with the vessel operation, and project team members.

3.3.1 Workshop Objectives

The objectives of the workshop for the Swedish service vessel case study were as follows:

- To present a high-level concept design for two zero-carbon propulsion options – NH_3 and H_2.
- To identify main hazards and possible mitigation measures for the NH_3 and H_2 propulsion option cases. This was to ensure that the main risk reduction measures would be considered in the environmental and cost assessment part of the project.

3.3.2 Workshop Scope

The following systems and spaces were covered during the workshop:

- Fuel storage system
- Fuel transfer system
- Fuel preparation space
- Fuel cell space

These are as depicted in Figure 8.

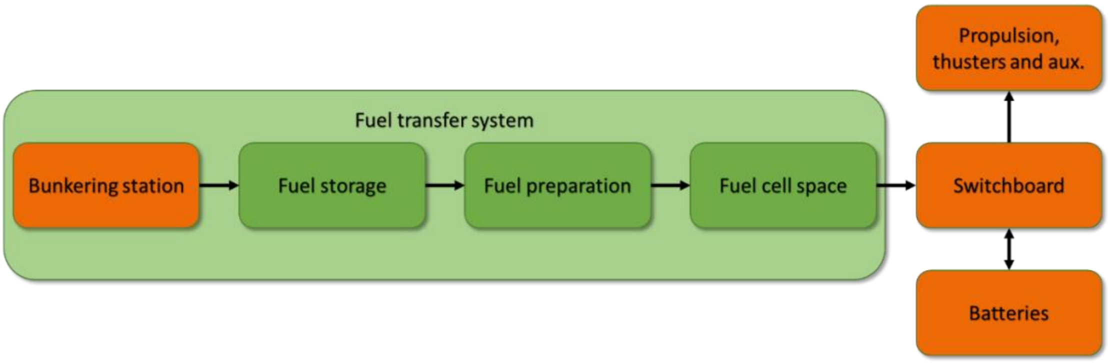


Figure 8:8 The system in focus for the safety workshop shown marked in green. Orange boxes are included for descriptive purposes.

The battery system and fuel cells were assumed to have undergone marine class approval and were not included in the hazard identification study. A time horizon of 2030 was assumed for the study, and it is expected that the fuel cell technologies will be fully mature at that time, although at the time of the workshop only H_2 fuel cells with this designation are commercially available. Bunkering activities were not covered.

3.3.3 Conceptual designs considered

Conceptual ship designs for H_2 and NH_3 fuel cell systems were developed based on a fully electric layout with fuel cells and batteries for supplying the ship with power. Two different types of fuels and fuel cells were proposed for the concepts: Proton Exchange Membrane Fuel Cells (PEMFC) using liquid H_2 from a cryogenic storage tank, and Solid Oxide Fuel Cells (SOFC) using liquid NH_3 from a compressed storage tank. Fuel was proposed to be stored in IMO Type C-tanks at -253 Celsius at 1 bar, and at ambient temperature at 10 bars, respectively. Conceptual designs were based on the current design, operational profile, and energy consumption of an existing service vessel operating in Swedish waters.

Details of the case vessel presented during the workshop were as shown in Table 3. The conceptual general arrangement considered during the workshop is shown in Figure 9.

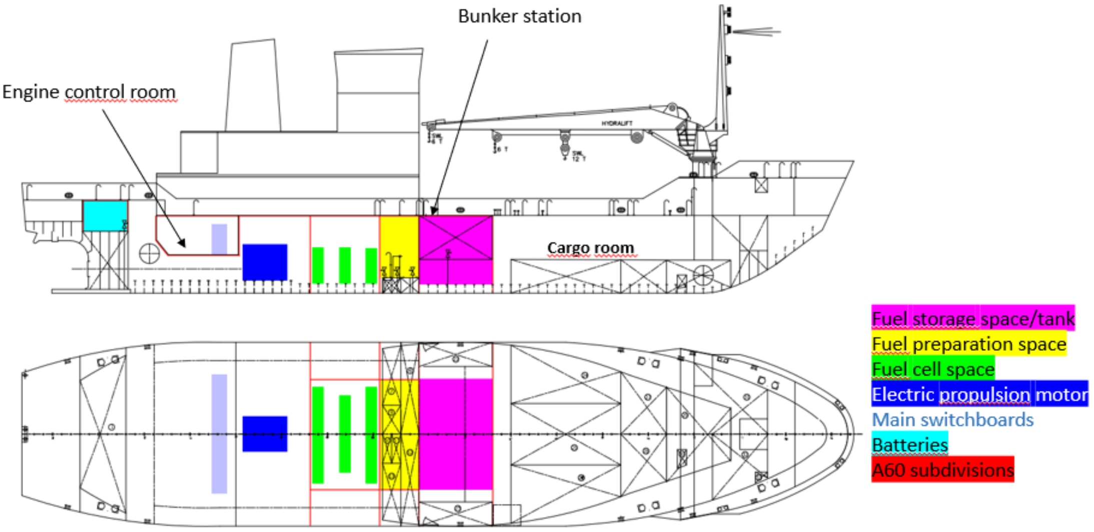


Figure 9: Conceptual general arrangement of the service vessel showing energy storage and main propulsion system components.

Table 3 – Case ship description including estimated operational profile and energy calculation.

<table>
<tr><th colspan="5">Ship details</th></tr>
<tr><td>Build year</td><td colspan="4">1983</td></tr>
<tr><td>Ship type</td><td colspan="4">Buoy Tender</td></tr>
<tr><td>Service speed</td><td colspan="3">15</td><td>knots</td></tr>
<tr><td>Length (OA)</td><td colspan="3">56.8</td><td>meters</td></tr>
<tr><td>Breadth(moulded)</td><td colspan="3">12.0</td><td>meters</td></tr>
<tr><td>Draught</td><td colspan="3">3.9</td><td>meters</td></tr>
<tr><td>Displacement</td><td colspan="3">1 238</td><td>tonnes</td></tr>
<tr><td>Main engines</td><td colspan="3">2 x 1 294</td><td>kW</td></tr>
<tr><td>Aux. gens.</td><td colspan="3">4 x 239</td><td>kW</td></tr>
<tr><td>Drive</td><td colspan="4">Gearbox connected to a single shaft CPP</td></tr>
<tr><td>Thrusters</td><td colspan="4">2 x Tunnel thruster (fore/aft)</td></tr>
<tr><th colspan="5">Estimated operational profile and average energy consumption</th></tr>
<tr><td rowspan="2">Bouy tendering</td><td colspan="3">~10 000</td><td>kWh/day</td></tr>
<tr><td colspan="3">149</td><td>days/year</td></tr>
<tr><td rowspan="3">Transit @ 12 knots</td><td colspan="3">~8 000</td><td>kWh/day</td></tr>
<tr><td colspan="3">27</td><td>days/year</td></tr>
<tr><td colspan="3">83</td><td>NM/day</td></tr>
<tr><th colspan="5">Energy calculation</th></tr>
<tr><td></td><td>[1] <i>Diesel</i></td><td>[2] <i>Liquid</i> H_2</td><td>[3] <i>Comp.</i> NH_3</td><td></td></tr>
<tr><td>Battery pack</td><td>None</td><td>[4] ~200</td><td>[4] ~200</td><td>kWh</td></tr>
<tr><td>Tank size</td><td>128</td><td>~80</td><td>~80</td><td>m3</td></tr>
<tr><td>Range @ 12 kn.</td><td>1 200</td><td>[5] ~110</td><td>[5] ~160</td><td>NM</td></tr>
<tr><td>Endurance (bouy tendering)</td><td>51</td><td>[5] ~3.1</td><td>[5] ~4.6</td><td>days</td></tr>
</table>

[1] – Average efficiency of 38.0%
[2] – Average efficiency of 53.5%
[3] – Average efficiency of 60.,0%
[4] – Estimated battery pack size based on similar ships with similar functions
[5] – At 70% net use of tank

3.3.4 Safety Assessment Methodology

Hazards were identified through a structured group review of the following main functional areas on the case study vessel: fuel storage system; fuel transfer system; and fuel cell space.

NH_3 and H_2 are both gases at ambient shipboard temperature and pressure, so the initial consideration was to identify hazards that can possibly lead to a gas release. Consequences were considered separately according to the properties of each gas. A brainstorming technique using "what if" prompt questions was used to stimulate the discussion. Causes, potential consequences, and possible safeguards were discussed. Comments, actions, and recommendations brought forward during the workshop were recorded in an Excel worksheet format.

3.3.5 Main results of the workshop

As the workshop object was a conceptual design, and two different gaseous fuels were considered in a single session, the discussion was limited to main hazards that could result in gas release. Due to the high-level nature of the discussion and limited time for the workshop, the findings should not be construed to represent all hazards that may be present.

A summary of the workshop discussion for the main functional area hazards covered is as follows:

Fuel Storage/Containment System:

- What if there is a collision or grounding?
    - For both H_2 and NH_3, IMO requirements for fuel tank placement of a minimum distance of B/5 from the side and the lowermost boundary of B/15 from the moulded line of the bottom shell plating were considered as the minimum existing safeguards to protect the tanks from damage.
    - The use of Type C tanks for NH_3 was considered acceptable and it was considered that these would prevent leakage along with the minimum placement requirements.
    - For the case study vessel, it was stated that there have been groundings in the past when the vessel was working in shallow waters, with some damage to tanks in the middle, but not to those in the stern area. The existing vessel does not have double bottom tanks – the additional protection as provided by B/15 should be in place for NH_3 and H_2 tanks.
- What if there are external or dropped objects hitting the tank(s)?
    - If the tanks are located below deck as shown in the conceptual design, there should be minimal probability of this. If the tanks are located on deck, there is the possibility of this occurring. This has not happened often in the past with the type of operations on the vessel. It should be ensured that the tank design and strength is adequate to prevent damage and that valves and fittings are protected.
- What if there is an external fire /over-pressurisation of tanks?

    - NH_3: For the type C tanks proposed for use, the design should be such that there are safety factors to withstand higher temperatures and pressure without venting, for a specified period of time. A suggestion was to consider design for the full vapour pressure of NH_3 at ambient temperatures (18 bar). This should be checked with more detailed design.
    - H_2: Comments from the workshop were that explosion risk of H_2 is high. A60 (60 minute) fire insulation around the fuel storage area may not be enough, so more protection should be considered. Ventilation or an inert environment for storage below deck should be investigated.
- What if there is a release of gas through venting?
    - NH_3: Current rule development by classification societies was said to be focusing on avoiding any venting of NH_3 during normal operations. A water-based scrubber system to remove NH_3 is currently considered as necessary.
    - H_2: H_2 is very light and any possibility for venting discharges should include checking requirements for hazardous area zones.

- **On deck versus under deck tank placement**: Some workshop participants felt strongly that storage of both H_2 and NH_3 should be on deck, rather than under deck as shown in the conventional design. Under deck storage was selected based on the current vessel design with cranes and three boats (lifeboat, large work boat, and small work boat) above deck. Some considered it would be easier to get approval for on-deck storage. This could apply to both NH_3 and H_2. With H_2, permeation through materials due to the small molecule size could lead to small releases. Positive aspects for under deck storage were noted to be easier detection of small leaks and more protection for the tanks.

<u>Transfer systems</u>:

- What if there is a collision or grounding?
    - Piping should be located a distance B/5 from the ship side, similar to the requirements for fuel tanks, to provide a minimum level of protection. For NH_3 the main consequence of concern for piping failure is the toxicity, while for H_2, it is the extreme flammability.
    - Double-walled piping should be used with detection in the annular pipe space. For NH_3 there should be a scrubber system to deal with any releases that enter the annular space. Vapour may be easier to deal with than liquid in the annular space – a recommendation was to consider trace heating for the NH_3 piping.
    - Piping requirements for LNG should be the starting point for both H_2 and NH_3. Further investigations are needed to determine whether this is sufficient.
- What if there are external impacts/dropped objects hitting the piping?
    - Resulting consequence could be damage to the pipes and leaks. Physical protection should be employed where needed. A workshop comment was that there is lots of experience with NH_3 and stainless-steel piping from other applications and it was recommended that best practices for other applications should be a starting point.
- What if there is an external fire in the vicinity of the piping?
    - H_2: Explosion risk is high so fire protection should be in place where there is risk of fire. A60 insulation was mentioned by workshop participants – further investigation is required.

- Other concerns such as limiting hot work or ignition sources such as mobile phones?
    - The hazardous area zone classification was considered as the existing safeguard for these risks. H_2 is highly flammable and although NH_3 is also a flammable gas it doesn't have the same ignition risk. Planning and risk assessment will help minimize risk. A gas alarm to cut power to different deck equipment could be considered.

Fuel Cell Space:

- What if there is a leakage of gas (NH_3 or H_2) inside the fuel cell space?
    - H2: The space should be classified as hazardous area zone 1 according to the interim guidelines for the safety of ships using fuel cell power installations. One commercial fuel cell provider supplies the system in a cabinet that acts as a secondary protection area and allows the remainder of the space to be considered non-hazardous.
    - H2 and NH_3: leakage detection is important for both. Ventilation also needs to be considered.

- What if there is a fire in the space?
    - H_2: Interim fuel cell guidelines state that the space should withstand a "local gas explosion". Special detectors are needed because the flame is invisible. UV or infrared detectors are options.
    - NH_3: The fire can be seen so detection is easier – however there are detector types specific to NH_3 available.
    - Appropriate fire extinguishing systems should be provided in the space, suitable to the technology and the fuel being used, according to the interim fuel cell guidelines.

3.4 Stability Safety Check

The intact stability of the case study vessels was checked with the new components and tank weights (both tank and fuel) and placement. This ensures that capsizing will not occur during the vessel's various loading conditions. Intact stability checks were done for the service ship and the tanker vessel with the liquid H_2 and compressed NH_3 systems.

4 Cost and environmental life cycle performance

The results based on the integrated life cycle analysis for all three case study vessels are summarized in Figure 10. The results are divided into five indicators:

1) Global warming potential (GWP) reduction compared to the conventional MGO case,
2) life cycle electricity demand based on electricity required over well to tank life cycle for delivering 1kWh of mechanical energy to the propeller,
3) other life cycle environmental impacts,
4) life cycle cost associated with the ship operation, and
5) carbon abatement cost that is cost associated with reduction one tonne of CO2eq from life cycle. Only decarbonization options that were found technically feasible are shown in the results.

Regarding GWP, for all ship types the assessed options could reduce climate impact significantly compared to the reference case with MGO (79- 92% GHG reduction potential). Results show that liquid H_2 in PEMFC has the highest GWP reduction potential for both the RoPax and service vessel cases. For the service vessel, the compressed H_2 in PEMFC has the second highest potential. Even though the fuel production stage has a lower impact for compressed H_2 than liquid H_2 options, the requirement of larger tanks onboard and at port counterbalances the downstream benefit. It may be noted that compressed H_2 options were found not feasible for the RoPax and tanker. NH_3 in SOFC was found to have the best potential for reducing emissions for the tanker and the second-best potential for reducing emissions for the RoPax vessel. Methanol in SOFC has the second-highest reduction potential for the tanker. In terms of safety, the use of NH_3 in RoPax may not be feasible considering the risk for the passengers onboard.

The life cycle electricity demand for decarbonization pathways based on e-fuels is significantly high. This is due to energy losses linked with conversion during upstream (production of fuel) and downstream (conversion to work) steps. Among all the assessed options, electro-methanol powered in the ICE pathway has the lowest energy conversion efficiency followed by the electro- NH_3 powered in the ICE pathway. This makes electro-methanol options more sensitive to the environmental and cost impacts of electricity than other options. This shows that a shift towards the e-fuels requires 2.5 to 3 times as much electricity as BE. This electricity demand is primarily driven by electrolysis. Hence, an energy transition of the shipping sector towards e-fuels will result in higher electricity demand and requires higher electricity generation capacity as well as infrastructure requirement for electricity transmissions.

Regarding other environmental impacts, LCA results show that all assessed systems significantly reduce the impacts of acidification, ecotoxicity, eutrophication (except for NH_3 options), ionizing radiation, land use, ozone depletion, particulate matter, photochemical ozone formation, and resource consumption (fossil). Nonetheless, a number of impact categories, including human toxicity (cancer and non-cancer), water use, and resource use (minerals and metals), are negatively affected, compared to MGO. The normalised values in Figure 10 shows that the NH_3 and methanol in engines (and liquid H_2 for the tanker) have the highest impact. This is primarily related to lower life cycle efficiency resulting in higher electricity use but also due to emissions due to use of pilot fuel and it need to be evaluated in more detail before drawing too strong conclusions. For NH_3, releasing of nitrogen-based molecules like NOx from combustion also need to be regulated.

LCC results as shown in Figure 10 shows that for all case ships, eNH3 followed by eMeOH has the lowest cost when used in the ICE. Compared to the reference case with MGO depending on assessed options, LCC is 2-3 times higher for the RoPax vessel, 2-4 times higher for the tanker, and 2-8 times higher for the service vessel. The major cost is associated with the fuel price for all technological systems except for batteries. The fuel cost is calculated along with the LCA assessment considering interdependencies between inventory parameters and electricity price. For batteries, the major cost is associated with the investment cost related to the battery system and the replacement required during the vessel's service life. Fuel cost is sensitive to electricity cost, hence the LCC cost will depend on the overall electricity demand (i.e., when the electricity cost increases, eMeOH in ICE will have a higher increase in cost than other options). The distribution and bunkering costs are high for the H_2 option and battery-electric propulsion as the infrastructure required is complex for these energy carriers.

Costs for different technological systems varies drastically between the assessed ship types, this is mainly associated with the annual energy consumption, installed capacity, and utilization rates. The effect of utilization rate can be observed clearly in the results of the service vessels, where the capital cost related to the component is prominent resulting in a higher cost for fuel cells and battery options. The same can be observed for the carbon abatement cost, that is NH_3 and MeOH used in ICEs have a lower abatement costs for all ship types. However the abatement cost varies widely with ship types. These variations depend on the utilisation rate as mentioned above, variation is least for the RoPax vessel (240 to 400 €/tCO_2eq) which have highest utilisation rate, and highest for service vessel (250 to 2000 €/tCO_2eq) which have lowest utililsation rate, This is because fuel cell and battery options have high investment cost and only high utilisation rates can compensate the fuel saved by increased efficiency.

A. Tanker

	Liquified H_2		Ammonia		Methanol		
	2SICE	PEMFC	2SICE	SOFC	2SICE	SOFC	
GWP reduction potential (% reduction)	79%	85%	79%	89%	82%	88%	🟩 >75% 🟨 50-75% 🟥 <50%
Energy Demand (kWh_{el}/kWh_{prop})	3.5	3.3	4.0	3.7	4.4	3.9	🟩 <2 🟨 2-4 🟥 >4
Other Environmental impacts (weighted value against MGO)	1.03	0.65	1.12	0.59	0.89	0.51	🟩 <0.6 🟨 0.6-0.8 🟥 >0.8
Life cycle cost (times MGO cost)	3.1	3.5	2.0	2.6	2.1	2.8	🟩 <2.5 🟨 2.5-5 🟥 >5
Carbon abatement cost (€/tCO2eq)	350	380	250	330	260	380	🟩 <350 🟨 350-500 🟥 >500

B. Service vessel

	Compressed H_2		Liquified H_2		Ammonia		Methanol		Battery electric	
	4SICE	PEMFC	4SICE	PEMFC	4SICE	SOFC	4SICE	SOFC		
GWP reduction potential (% reduction)	82%	89%	83%	90%	79%	88%	82%	86%	74%	🟩 >75% 🟨 50-75% 🟥 <50%
Energy Demand (kWh_{el}/kWh_{prop})	3.5	3.1	3.7	3.3	4.3	3.2	4.8	3.9	1.3	🟩 <2 🟨 2-4 🟥 >4
Other Environmental impacts (weighted value against MGO)	0.66	0.57	0.63	0.54	0.98	0.74	0.86	0.67	1.16	🟩 <0.6 🟨 0.6-0.8 🟥 >0.8
Life cycle cost (times MGO cost)	2.5	4.8	2.0	4.5	1.8	7.0	1.8	7.3	5.8	🟩 <2.5 🟨 2.5-5 🟥 >5
Carbon abatement cost (€/tCO2eq)	460	1080	330	980	250	1810	260	1880	1660	🟩 <350 🟨 350-500 🟥 >500

C. RoPax vessel

	Liquified H_2		Ammonia		Methanol		Battery electric	
	4SICE	PEMFC	4SICE	SOFC	4SICE	SOFC		
GWP reduction potential (% reduction)	85%	92%	81%	92%	84%	91%	91%	🟩 >75% 🟨 50-75% 🟥 <50%
Energy Demand (kWh_{el}/kWh_{prop})	3.7	3.3	4.3	3.2	4.8	3.9	1.3	🟩 <2 🟨 2-4 🟥 >4
Other Environmental impacts (weighted value against MGO)	0.57	0.45	0.97	0.55	0.85	0.48	0.39	🟩 <0.6 🟨 0.6-0.8 🟥 >0.8
Life cycle cost (times MGO cost)	2.5	2.8	2.1	2.6	2.2	2.8	2.2	🟩 <2.5 🟨 2.5-5 🟥 >5
Carbon abatement cost (€/tCO2eq)	350	380	250	330	260	380	240	🟩 <350 🟨 350-500 🟥 >500

Figure 1010: LCA and LCC results from the study for case vessels simplified into three color scales based on relative values A) results for the Tanker, B) results for the Service vessel, and C) results for the RoPax vessel.

For the same energy carrier, it is interesting to compare engines and fuel cells from the perspective of the ship's system. Without defining the most important criterion for selection, it is difficult to determine a clear winner. Figure 11 illustrates important aspects to consider when choosing between engines and fuel cells in shipping. Fuel cells have considerable advantage over ICEs when comparing the

GWP, other environmental impact and life cycle energy demand. However, the main disadvantage for fuel cells is the associated cost. High utilization rate can lead to savings in the fuel cost and thereby may be able to offset the investment costs. Except for the higher utilization rate, fuel cells would become more competitive than ICEs at higher fuel costs (it may also be noted that it is assumed that cheaper MGO is considered for ICE options as pilot fuel). The fuel cost is sensitive to electricity prices and hence fuel cell competitiveness depends on the electricity price. See Kanchiralla et al. [20] for detailed sensitivity analysis with electricity cost.

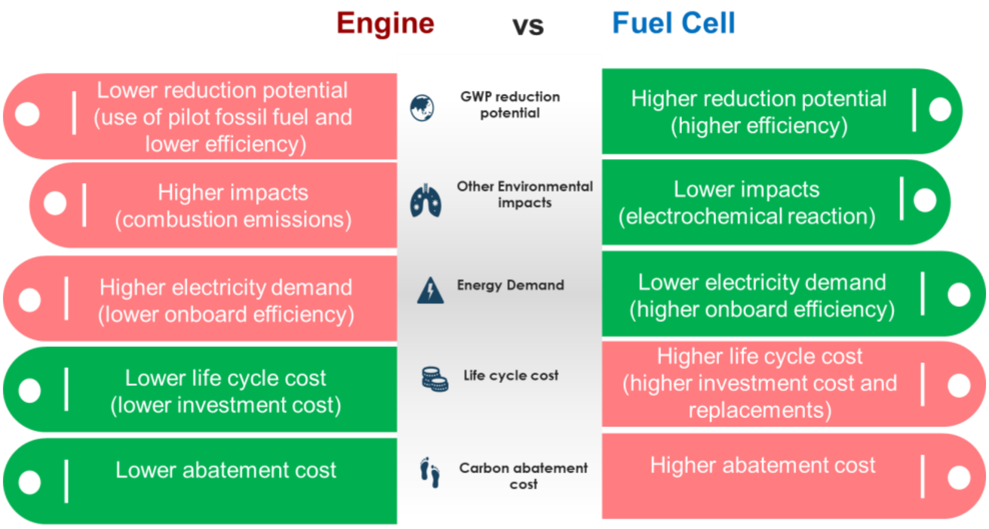


Figure 11 Comparison of internal combustion engine and fuel cells.

5 Discussion

NH_3, H_2, and battery-electric propulsion all have pros and cons for use in maritime transport. The pro is related to that they can be produced with very low climate impact under the right conditions. The cons are related to risk and safety concerns especially for NH_3 and H_2, and to lower energy density than HFO and MGO. From a ship system perspective, a battery system and H_2 system both need more volume and weight onboard for the same journey. Volume constraint is due to low volumetric energy densities for both options, but mass constraint for H_2 is primarily because of complex vacuum cryogenic tanks and for batteries due to lower gravimetric energy densities.

5.1 Result discussion

Regarding the fuel production pathways, there are three main production pathways for H_2 and NH_3: fossil pathway (with and without carbon capture), biogenic pathway (not yet very well explored) and electricity pathway. Within this project the main focus has been on the electricity pathway (i.e., the electrofuel pathway). The climate impacts from fuels produced from electricity is dependent on the carbon intensity of the electricity used. With renewable power such as wind power very low climate impacts can be achieved. However, the life cycle assessment has also indicated that there are some potential environmental concerns where the environmental impact could be higher than for MGO and HFO such as human toxicity, water use, and resource use (minerals and metals). These impacts are primarily associated with materials used in infrastructure (wind power, fuel infrastructure) and ship components. The possibility of reducing these impacts may be investigated further, for instance, by examining how a higher proportion of recycled materials in the infrastructure and components can reduce these impacts.

NH_3 fuel combustion in engines has a in some cases higher climate impact than methanol and H_2 and has higher potential impact on eutrophication. The higher climate impact is associated with emissions of nitrous oxides (nitrous oxide (N_2O) is a stronger GHG than methane and CO_2) and the eutrophication impact with emissions of nitrogen oxides and NH_3. As NH_3 engines are still in the development phase, more knowledge on emissions is required. Understanding these emissions at an early stage helps to avoid potential environmental impacts by means recognizing the need to use abatement technologies like SCR.

When comparing the life cycle cost, NH_3 and methanol have an advantage over H_2 and battery-electric propulsion. This is especially due to their higher volumetric energy densities compared to batteries and H_2, which results in lower cost of transportation and bunkering. However, for battery-electric propulsion both the cost associated with the charging infrastructure and the cost of the batteries are critical. However, battery-electric propulsion has the lowest life cycle cost for cases with low battery prices, and when a relatively small battery size is possible and better utilization of charging infrastructures is possible (e.g., for short routes when it is possible to charge the battery frequently).

Compared to other transport sectors, the carbon abatement costs for shipping are higher (>250€/tCO2eq) reinforcing the argument that shipping is a hard to abate sector. As shown in the results, the main element of cost for the electrofuel pathways is the fuel cost. The electricity cost, energy conversion efficiency upstream and the infrastructure cost determine the cost of the electrofuels (it may be noted that shipping sector currently operates with cheaper fossil fuels than fuels used in road or aviation [21]).

Regarding safety, NH_3 and H_2 are both gases at ambient shipboard temperature and pressure, which requires additional safety considerations and strategies as compared to traditional liquid fuels. H_2 is an extremely flammable gas, while the main hazard with NH_3 is the high toxicity to humans and to the environment. Fuel storage and distribution systems therefore need to be designed to ensure no release and an extra barrier (such as double walled piping) is required. Hazardous area zone designation is important for both gases and early leak detection is a key tool for ensuring safety.

Each option has different complexities depending on the specific ship (linked to the design and function of the vessel and its operation). These differences are both from the fuel production side and ship system. For fuel production side, the main parameters are the carbon intensity of electricity mix, electricity cost, complexity in bunkering, electricity required for fuel synthesis, and location of fuel production sites (not investigated in the report). For ship system side the choice depends on three main parameters: 1) installed capacity of energy converters (depending on designed operation profile), 2) energy use between bunkering which determines the size of the energy storage required, 3) amount of energy used per installed capacity or utilisation rate. Installed capacity is important while assessing fuel cell options because the higher installation capacity means more fuel cells need to be installed onboard. Due to lower energy density and higher storage costs, the second parameter regarding energy between bunkering is significant for H_2 and battery electric (i.e., more energy required between bunkering means larger energy storage is required). For fuel cell systems and battery electric, a higher utilization rate would offset the higher cost of the propulsion system by lower fuel consumption due to higher efficiencies.

5.2 Putting the result in context

There is a potential to decarbonize the shipping industry by changing energy carriers to H_2, NH_3, or electricity. This project illustrates that it is possible to substantially reduce the GHG emission/climate impact by introducing NH_3, H_2, and battery-electric propulsion. However, even if these fuels are free from carbon atoms, they are not necessarily free from CO_2 emissions at the ship as they in some propulsion systems need pilot fuels which could contain carbon, and they are still associated with GHG emissions and other environmentally damaging emissions during their life cycle when fuels are produced and distributed, and infrastructure built.

Brynolf et al. [22] showed that it will be difficult to reach completely zero climate impact from marine fuels by 2030 in a LCA perspective investigating 32 pathways. Brynolf et al. [22] compared green pathways (defined as electrofuels and biofuels) with blue pathways (defined as natural gas-based fuels with carbon capture during production). Generally, it was shown possible to receive lower GHG emissions/climate impact with green pathways than for the corresponding blue pathways. The study also suggested that it is possible to provide very low climate impact for most of the assessed pathways when/if the society transform to a low GHG society (around 2050) and also steel, cement and electricity production will reach zero or close to zero carbon emissions. Thus, there is a clear link between environmental performance of marine fuels and propulsion systems and the development in other sectors and industries.

Critical aspects for reducing climate impacts in Brynolf et al. [22] were identified as (i) increased share of renewable energy in the electricity mix (mainly for the electrofuel fuel production pathways), (ii) the use of solid-oxide electrolysers used for H_2 production (if they manage to achieve expected efficiency) instead of alkaline electrolysers, (iii) reduced impact from production of materials used for propulsion systems, storage etc., (iv) renewable urea instead of natural gas-based urea in selective catalytic reduction units, (v) lower assumed emissions of N_2O and CH_4 for the cases where NH_3 and methane was used as energy carrier. Figure 13 illustrates the climate impact for a broad set of fuels and propulsion systems and is based on the work in this study as well as Brynolf et al. [22] and Brynolf [23] to put the assessments in this report in context.

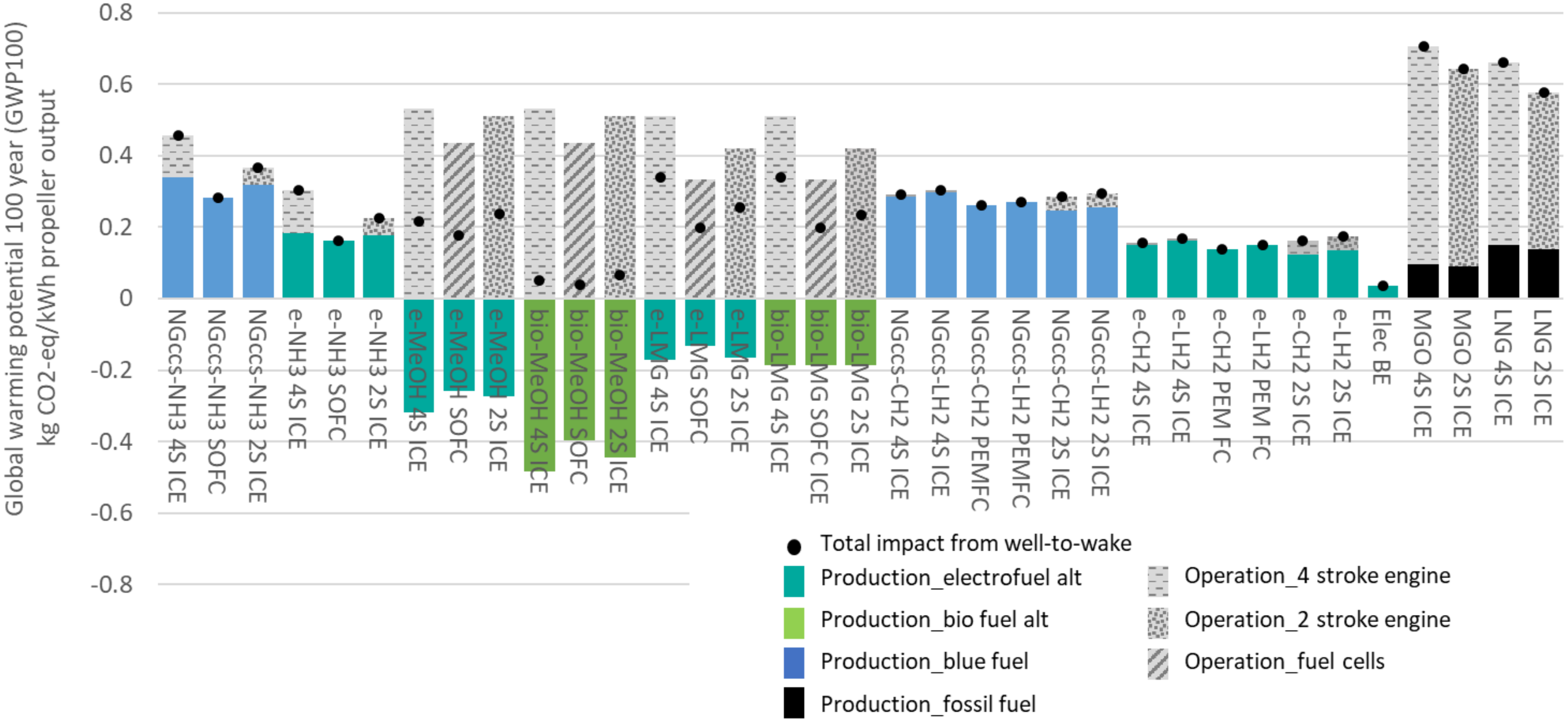


Figure 12 Global warming potential (in kg CO_2-eq.) in a 100-year time perspective for the investigated potential zero-carbon fuels in Nordic shipping in 2030 for 1 kWh propeller output. The global warming potential is illustrated for fuel/energy carrier production including distribution and transport (and for the battery-electric option the production of electricity) and for operation onboard the ship. ***The dots represent the net value from well-to-wake****. NGccs - steam reforming of natural gas with carbon capture and storage, NH3 - ammonia, 4S – 4-stroke engine, 2S – 2-stroke engine, ICE – internal combustion engine, SOFC - solid oxide fuel cell, e-NH3 – electro-ammonia, e-MEOH – electro-methanol, bio-MEOH – biomass based methanol, e-LMG – electro-methane, bio-LMG-liquified biogas, CH2 – compressed hydrogen, LH2 – liquefied hydrogen, PEMFC – Proton-exchange membrane fuel cell, Elec-BE – Battery Electric, MGO – marine gas oil, LNG – liquefied natural gas. For full description of the assessed pathways see Brynolf et al. [22]. The bio-LMG data is added here with production data for the bio-LMG pathway is added from Brynolf [23]. Note that the pilot fuel in Brynolf et al. [22] is considered as hydrotreated vegetable oil (HVO).*

5.3 Recommendations

The development of LCA methodology for marine fuels in the IMO has been on the agenda during the project and the first provisional guidelines were approved at MEPC80 [24]. Data generated during this project and in the project "Nordic Roadmap for the introduction of sustainable zero-carbon fuels" (https://futurefuelsnordic.com/) has been used to illustrate the IMO guideline methodology [25].

From the environmental assessments done in this project we find some important points when developing LCA methodology for marine fuels:

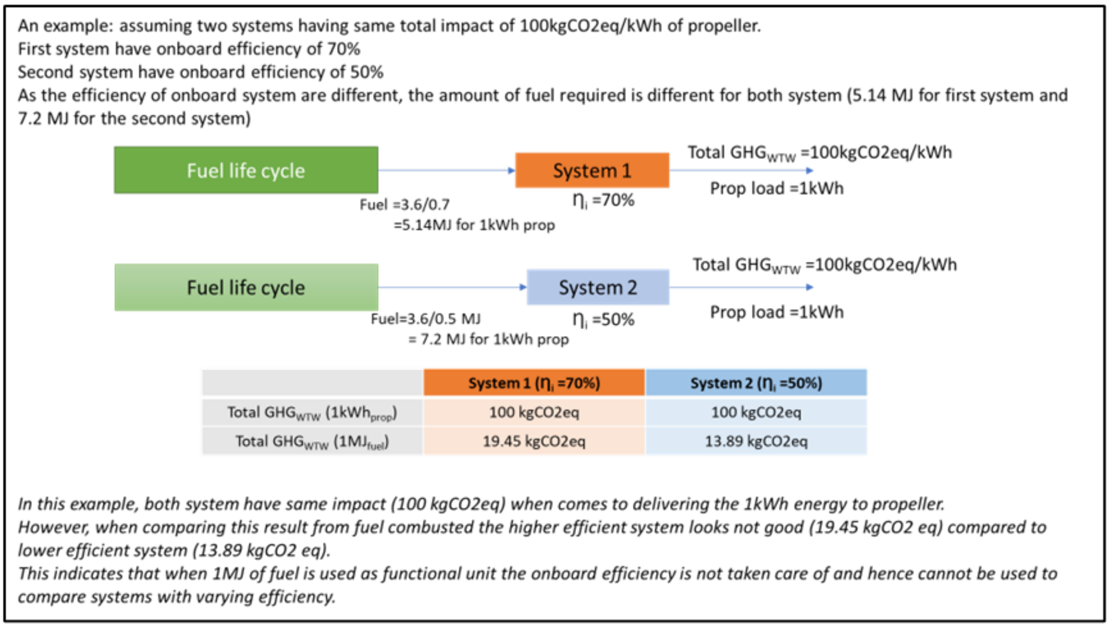
- Accounting for all carbon flows
- Important to consider the efficiency of the energy converter onboard the ship in LCAs of marine fuels and propulsion systems when comparing different options.
- A broad set of environmental impact categories
- Include the production of infrastructure in the system boundaries.

It is important to account for all carbon flows both biogenic and fossil when evaluating the climate impact of marine fuels and propulsion systems to increase transparency and comparability.

It is important to consider the efficiency of the energy converters onboard the ship in LCAs of marine fuels and propulsion systems when comparing different options. A functional unit of 1 MJ combusted fuel cannot be used to compare options where the efficiency of the propulsion system differs. For the same amount of combusted energy different propulsion can be provided dependent on the efficiency of the propulsion system. Below is an example showing that comparing GHG intensity per MJ fuel can can lead to a faulty understanding of the GHG intensity of different options (Figure 15). However, a functional unit of combusted energy can be good if the main purpose of the data is to provide data for other actors to use in their assessment. As an example, can the emissions per MJ fuel combusted be multiplied with the actual amount of fuel combusted to get the total emission.

It is important to consider a broad set of environmental impact categories when evaluating fuels and propulsion systems as different options have different environmental hot spots.

It is important to include the production of infrastructure in the system boundaries. However, these impacts are also important and can be considerable for some renewable options. This is for example the case for electrofuels produced from renewable electricity as shown in this project.



An example: assuming two systems having same total impact of 100kgCO2eq/kWh of propeller.
First system have onboard efficiency of 70%
Second system have onboard efficiency of 50%
As the efficiency of onboard system are different, the amount of fuel required is different for both system (5.14 MJ for first system and 7.2 MJ for the second system)

	System 1 (η_i =70%)	System 2 (η_i =50%)
Total GHG_{WTW} ($1kWh_{prop}$)	100 kgCO2eq	100 kgCO2eq
Total GHG_{WTW} ($1MJ_{fuel}$)	19.45 kgCO2eq	13.89 kgCO2eq

In this example, both system have same impact (100 kgCO2eq) when comes to delivering the 1kWh energy to propeller.
However, when comparing this result from fuel combusted the higher efficient system looks not good (19.45 kgCO2 eq) compared to lower efficient system (13.89 kgCO2 eq).
This indicates that when 1MJ of fuel is used as functional unit the onboard efficiency is not taken care of and hence cannot be used to compare systems with varying efficiency.

Figure 13: An example illustrating the importance of considering the energy converter efficiency in LCA methodology for developing marine fuels and propulsion system.

From the environmental and cost assessments done in this project it is shown that it is important to introduce policy measures that makes it possible to invest in renewable options in all parts of the life cycle of marine fuels. This study's estimate of the carbon abatement cost indicate that policies might need to penalize GHG emission with at least 250–300 €/tCO_2eq.

There is a need of new sustainable fuels to be produced and to build ships that can use the sustainable fuels. There is also a need to continuously invest in monitoring and measurement to increase the performance of the new fuel and propulsion technologies as well as a need for updated environmental assessments when new data is available.

5.4 Future work

Often comparability of life cycle analyses is difficult without knowing the underlying assumption and definitions. This can be depicted like an iceberg as illustrated in Figure 16. It is challenging to understand the underlying methodology and assumption of LCA and LCC. In this study, methodological challenges associated with goal and scope definition and inventory assumptions for emerging technology are addressed by including different tools as mentioned in Section 2. However, including development of the production of fuels and variations in operation of ship over time (dynamic assessment) is another challenge not addressed in this study. The generalizability of the results found for changes in environmental impact in relation to MGO need to be assessed further. Are the findings relevant for more updated production processes with potentially newer impact data than in the LCA database? Also, new coming data for emissions linked to the emerging marine fuels, when tested are also crucial to consider and use in updated LCA assessments in to further confirm the findings in this study. As indicated some impacts are not yet very well known. Another challenge is identifying the possibility of a new environmental problem not known now. One such indicator may be marine ecotoxicity like freshwater ecotoxicity which would be relevant for ships.

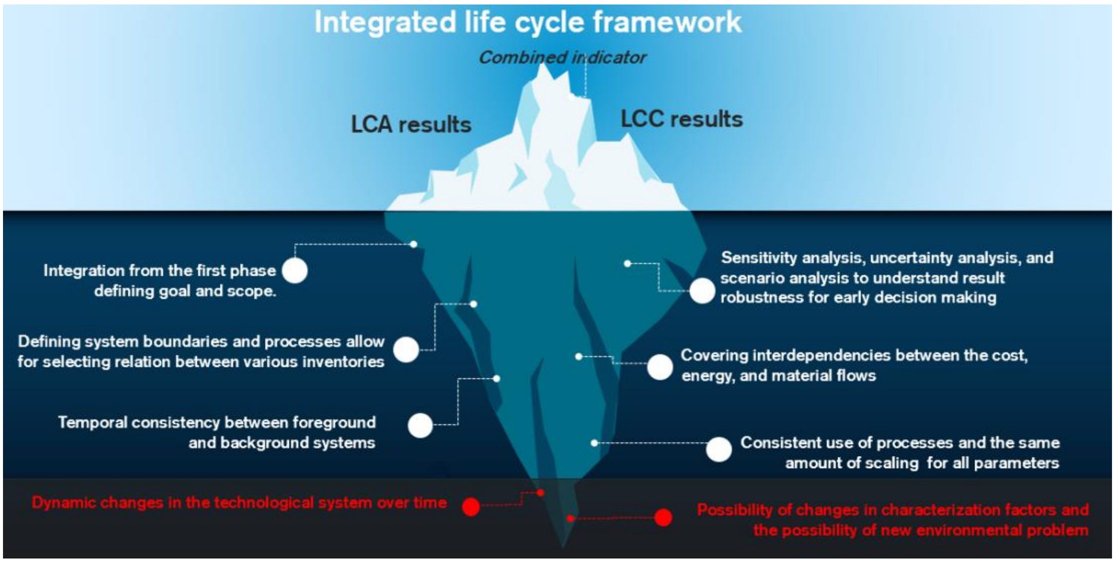


Figure 14: Illustartion of the integrated life cyckle framwork with aspects adressed in this project in white and remainging challenges in red.

According to the findings of this study, the transition towards decarbonization of the shipping industry will not be uniform for all vessels. Consequently, the proportion of each fuel used in a fleet will vary depending on vessel operation and type. To comprehend the needs of the supply chain, port infrastructure, etc., it is necessary to know how different fuels will evolve and be introduced. Integrating additional tools, such as modelling global energy systems with a life cycle framework, could enable the development of future scenarios for the transition of fleet-level energy carriers.

Another aspect is the indirect climate impacts connected to emissions of H_2 [26, 27]. These are not considered in this project, but they should be included in future studies to make sure that potential leakages in the H_2 supply chain will not change the climate impact of H_2 pathways significantly.

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