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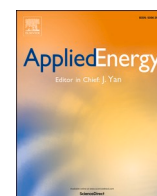
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How do variations in ship operation impact the techno-economic feasibility and environmental performance of fossil-free fuels? A life cycle study

Fayas Malik Kanchiralla [a,*], Selma Brynolf [a], Tobias Olsson [b], Joanne Ellis [b], Julia Hansson [a,c], Maria Grahn [a]

[a] *Chalmers University of Technology, Department of Mechanics and Maritime Sciences, Hörselgången 4, SE-412 96 Gothenburg, Sweden*
[b] *Research Institutes of Sweden, Maritime Department, Chalmers Tvärgata 10, SE-412 58 Gothenburg, Sweden*
[c] *IVL Swedish Environmental Research Institute, SE-411 33 Gothenburg, Sweden*

HIGHLIGHTS

- How vessel operation will affect the environmental impacts of different decarbonization options is presented.
- Technical feasibility of selected fuel and propulsion systems for three different types of vessels are investigated.
- Economic tradeoffs for selecting different decarbonization pathways considering climate impact reduction potential, and.
- LCA and LCC results are performed for two different electricity scenarios.

GRAPHICAL ABSTRACT
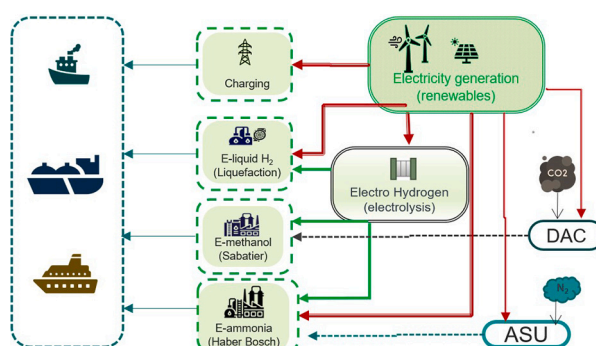
ABSTRACT

Identifying an obvious non-fossil fuel solution for all ship types for meeting the greenhouse gas reduction target in shipping is challenging. This paper evaluates the technical viability, environmental impacts, and economic feasibility of different energy carriers for three case vessels of different ship types: a RoPax ferry, a tanker, and a service vessel. The energy carriers examined include battery-electric and three electro-fuels (hydrogen, methanol, and ammonia) which are used in combination with engines and fuel cells. Three methods are used: preliminary ship design feasibility, life cycle assessment, and life cycle costing. The results showed that battery-electric and compressed hydrogen options are not viable for some ships due to insufficient available onboard space for energy storage needed for the vessel's operational range. The global warming reduction potential is shown to depend on the ship type. This reduction potential of assessed options changes also with changes in the carbon intensity of the electricity mix. Life cycle costing results shows that the use of ammonia and methanol in engines has the lowest life cycle cost for all studied case vessels. However, the higher energy conversion losses of these systems make them more vulnerable to fluctuations in the price of electricity. Also, these options have higher environmental impacts on categories like human toxicity, resource use (minerals and metals), and water use. Fuel cells and batteries are not as cost-competitive for the case vessels because of their higher upfront costs

and shorter lifetimes. However, these alternatives are less expensive than alternatives with internal combustion engines in the case of higher utilization rates and fuel costs.

1. Introduction

The shipping sector is key for international trade and is responsible for about 3% of the total anthropogenic greenhouse gas (GHG) emissions [1] and also the emission of other air pollutants like sulfur oxides, nitrogen oxides, particulate matter that have a significant negative impact on the natural environment and human health [2,3]. Considering the projected increase in maritime trade [1], to meet the International Maritime Organization's (IMO) 50% absolute GHG reduction target by 2050 [4], a GHG emission intensity reduction of 75–85% per tonne-km [5] is required. To achieve GHG emission intensity reduction, a paradigm transition towards ships that operate with low climate impact fuels or propulsion systems is needed. Low climate-impact fuels can be based on biomass (biofuels) or renewable electricity (including e-fuels also called electro-fuels, power-fuels, etc.) or both (bio-electro fuels) [6] or fuels produced by reforming or gasification of fossil fuels in combination with carbon capture and storage (CCS) (blue-fuels) [7]. *E*-fuels in shipping have received considerable attention due to high feedstock availability compared to biofuels which depend on biomass availability [11] and blue fuels which depend on fossil fuels.

This study focuses on e-fuels which are defined as synthetically produced energy carriers that contain electrolytic hydrogen (H_2) (produced by electrolysis of water using electricity) directly or chemically bonded with carbon (e.g. methanol (MeOH)) or nitrogen (e.g. ammonia (NH_3)) using electricity [8–10]. Unlike present fossil-based fuels like heavy fuel oil (HFO) or marine gas oil (MGO) which have a high volumetric and gravimetric energy density, the e-fuels included in this study have different properties in terms of energy density (volumetric and gravimetric), storage parameters, flammability, toxicity, etc., hence the choice of e-fuel would vary depending on vessel function. Based on vessel functionality, IMO has categorized the ships into nineteen ship types and further categorized them based on their size into 'size bins' [1]. With variations in function, voyage, operation style, and design of the ship, the fuel consumption, space, or weight availability for different energy carriers differ between ships. This diversity in the vessel's functionality would have different implications for each energy carrier and would affect the most suitable e-fuels. For example, longer voyages and high fuel consumption per trip are key factors when deciding the amount of fuel storage and the powertrain system components required in the ship which may have a higher impact on the fuels with lower energy density from a system perspective.

E-fuels are evaluated in studies for energy utilization [5,11], environmental impacts using life cycle assessment (LCA) [12–15], and cost assessment [11,12,16,17]. There are studies that evaluated the cost of different e-fuels on different vessel types [18–20]. For example, Korberg et al. [18] have evaluated the cost of ownership for various fuels including e-fuels for large ferries, general cargo, bulk carriers, and container vessels, and found MeOH to be a cost-effective solution for all ship types, but the operational profile of the ships are not considered in the assessment. Horvath et al. [20] have performed techno-economic assessments of short-sea, deep-sea, and container vessels and found hydrogen used in fuel cells (FC) to be a cost-effective choice. None of the above studies have included cradle-to-grave life cycles or considered the operational profile of the ships. Kanchiralla et al. [12] have performed both LCA and life cycle costing (LCC) from cradle to grave and have included an operational profile within the analysis and found that ammonia in FC is an effective choice in terms of carbon abatement cost. However, that study was limited only to the operation of a roll-on-roll-off-passenger (RoPax) vessel and did not include an assessment of technical feasibility. There are knowledge gaps on the life cycle impacts and feasibility of different decarbonization options for various ship types.

This study aims to contribute to this knowledge gap by analyzing the ship design feasibility, LCA, and LCC of three case study ship types for different fossil-free energy carriers. The main research question explored in this study is: "How significantly does the environmental and economic performance of various decarbonization pathways, such as battery-electric and electro-fuels, vary for different ship types, including RoPax vessel, tanker, and service vessel?". This knowledge is not only relevant for ship owners and operators for increasing understanding of the performance of selected decarbonization solutions for individual ships but also for academicians and policymakers for developing a fleet-level model and overarching policies.

In this study, both internal combustion engine (ICE) and FC-powered propulsions are considered for the e-fuels H_2, NH_3, and MeOH in addition to battery-electric (BE) operation. Preliminary designs of the options are detailed in Section 3.2. Since the decarbonization technologies considered in the study are still under development, prospective scenarios are considered for evaluation. Prospective scenarios in this study are built based on scaling emerging technologies to an operational scale based on literature data and expert opinions. MGO is also included for comparison. The options that were found infeasible after the feasibility analysis are not considered for LCA and LCC analysis. Regarding the safety aspect of the alternate fuels onboard, hazard statements according to the United Nations Globally Harmonized System of Classification and Labelling of Chemicals (GHS) for ammonia are 'flammable gas', 'toxic if inhaled', 'causes severe skin burns and eye damage (corrosive)' and 'very toxic to aquatic life'. The hazard statement for hydrogen is 'extremely flammable gas' [21]. The hazard statements for methanol are "highly flammable liquid and vapor" and 'toxic if swallowed, inhaled, or in contact with skin' [21].

This study is novel in its comparison of the environmental impacts of various decarbonization pathways using life cycle assessment for three different case vessel types with different operational profiles. It also compares the carbon abatement cost for different ship types for e-fuels and BE options and includes MeOH fueled in solid oxide fuel cells (SOFC) as a decarbonization option. Environmental impacts are assessed per transport work (dead weight tonnage km (DWT-km) or gross tonnage km (GT-km)) of the ship, similar to the carbon intensity indicator (CII).

2. Methodology

2.1. Case study ships

Three case study ships are selected to illustrate the diversity of ships in functions and operations and how this can impact the choice of fuels and propulsion systems and their respective costs and environmental performance. Tankers are one of the most energy-consuming ships in deep-sea shipping, whereas the RoPax category is one of the largest vessel fleets in short-sea shipping in terms of emissions [1]. The profile of a service vessel, representing a smaller ship type, is regarded as being entirely distinct and hence included in the study. The details of the three different ships considered for the assessment are summarized in Table 1. The first ship is a tanker that operates between Point Lisas in Trinidad & Tobago, and Singapore crossing the Pacific Ocean and back carrying a liquid payload. The second ship is a service vessel operating in Swedish waters engaged in fairway maintenance and ice-breaking activities, each of which has different daily operational profiles. The third ship is a RoPax vessel (taken from [12]), which travels on a fixed route between Gothenburg (Sweden), and Kiel (Germany) which is 230 nautical miles one way used for freight vehicle transport along with passenger

Table 1

Characteristics of the case study ships assessed in the study.

Ship type	Chemical tanker	Service vessel	RoPax vessel
Deadweight tonnage (DWT)	49,900	361	10,130
Lightweight tonnage (NDT)	11,269	940	10,580
Gross tonnage (GT)	29,884	980	52,000
Length (m)	186	56.76	240
Installed main engine (kW)	5700	2588	20,000
Installed aux generator (kW)	1050	928	4000
Number of trips annually	4 round trips	Daily operation	182 round trips
Service life (years)	25	40	30
Service speed (knots)	14.5	15	19
Operation profile: Annual energy use (kWh)			
Propeller load (cruising)	26,150,000	1,376,000	69,615,000
Propeller load (maneuvering)	326,900	159,000	4,076,800
Auxiliary electrical load (cruising)	6,320,000	506,000	5,751,200
Auxiliary electrical load (cruising)	79,000	58,000	1,055,600
Thermal load (maneuvering)	39,000	–	5,678,400
Thermal load (cruising)	500	–	910,000
Electrical load at ports (mooring)	–	566,400	3,967,600

accommodation.

2.2. Investigated energy carriers and technologies

This study assesses e-fuels produced mainly from renewable electricity in addition to direct electrification (BE). Six energy carrier production pathways are included: electricity (for BE), compressed hydrogen (eCH$_2$), liquefied hydrogen (eLH$_2$), electro-ammonia (eNH$_3$), and electro-methanol (eMeOH) (see Fig. 1A). These alternative fuels are combusted in FCs or ICEs to power the ship. Fig. 1A shows the fuel production pathways and Fig. 1B shows the propulsion system configuration considered in this study.

The type of FC used is decided based on the energy carrier, the proton-exchange membrane FC (PEMFC) is considered when using H$_2$ directly (eCH$_2$ and eLH$_2$), and solid oxide FC (SOFC) is considered for NH$_3$ and MeOH. In this study, the option of cracking the e-fuels to generate hydrogen and using the hydrogen in PEMFC is not considered as the overall system efficiency decreases with cracking and purification and demands more components onboard [22]. Another option not considered is using H$_2$ in SOFC, as the electrical efficiency of hydrogen (in SOFC) would be lower due to the higher difference between Gibbs energy and enthalpy change and also due to high parasitic losses during operation compared to other fuels [23]. The FCs for the vessel were sized based on the power requirements, however, during startup and power ramping, a battery stack is considered for FC configuration. For PEMFC, the battery is sized to store enough energy required for 10 min of operation at an engine load of 20% and for SOFC, the battery is sized for 30 min of operation at an ICE load of 20%. Unlike PEMFCs, a battery for longer operation is considered for SOFC as they are slow to respond and require a long start-up time. While in operation, this additional battery system can be used to compensate for the peak load by energy management, hence required power capacity of PEMFCs and SOFCs can be reduced. A detailed optimization calculation is not performed in this study, but a 10% reduction in power capacity is assumed for FC configuration as batteries sized for 20% load are available for peak management (this is a simplified assumption).

The choice of ICE for each ship is based on today's common options, hence a 4-stroke (4S) ICE is considered for the RoPax and service vessels, and a 2-stroke (2S) for the chemical tanker. ICEs with dual fuel configuration are assumed for all fuels including hydrogen (different

compared to the study by Kanchiralla et al. [12] which assumed spark ignition ICEs), and to maintain good combustion for the fuels, a pilot fuel is required which is assumed as MGO. It may be noted that the efficiency and emissions would change with the type of ICE and with the choice of fuel (detailed in Section 4). Considering that these ships operate partially or completely in the emission control area (ECA), it is assumed that the ship is equipped with SCR for NOx abatement to meet Tier III requirements (all 2S ICEs and 4S ICEs fueled by NH$_3$, and MGO) as shown in Table 3. A total of 10 scenarios with various fuel and propulsion configurations are investigated in the study including reference cases for each ship: 1) eNH$_3$ in dual-fuel ICE and MGO as the pilot fuel (eNH3ICE), 2) eNH$_3$ fueled in SOFC (eNH3SOFC), 3) eMeOH fueled in dual-fuel ICE and MGO as the pilot fuel (eMeOHICE), 4) eMeOH fueled in SOFC (eMeOHSOFC), 5) eCH$_2$ fueled in dual-fuel ICE and MGO as the pilot fuel (eCH2ICE), 6) eLH$_2$ fueled in dual-fuel ICE and MGO as the pilot fuel (eLH2ICE), 7) eCH$_2$ fueled in PEMFC (eCH2PEMFC), 8) eLH$_2$ fueled in PEMFC (eLH2PEMFC), 9) electric-propulsion using electricity stored in batteries (BE), and 10) MGO fueled in ICE (MGOICE). As per the configuration shown in Fig. 1B, the component parameters for three case study ships used in the assessment are detailed in Table 2.

2.3. Technical design feasibility

The technical viability of the decarbonization pathways is assessed by comparing the volume and weight of the propulsion system to the existing engine, fuel storage, and mechanical space of the case vessels. The power capacity of the components for each configuration is also considered, based on the downstream efficiency of the options. The storage tank capacity for the options is based on the energy required between bunkering based on the case-specific voyage and the efficiency of the propulsion system.

The following approach is used for the analysis: first, calculate the propeller energy load, auxiliary electrical load, and thermal load for each case ship based on the installed equipment rating, sea margin (difference in power required in operational conditions compared to the calm water conditions), and energy required for the maximum fuel-consuming voyage. To create a common basis for comparison, the same ship structure and operation were used for all concepts for each case vessel. For the tanker and service vessels, general arrangement drawings, installed main engine power, and auxiliary power were provided by the ship owner. The tanker vessel operation detail is not available, so the energy loads were calculated based on design details, route, and likely operation speed. These values were then multiplied by the sea margins. For the service vessel, the data on fuel and energy consumption from the engines along with the activity datasheet obtained from the ship operator is used to calculate the energy profile. This data is then developed with the help of Automatic Identification System (AIS) data for the same period. Information on the thermal load for the service vessel was not available. For the RoPax vessel, the operation profile, and installed powertrain configuration, were taken from [12].

Second, for all three vessels, the amount of energy carrier that needs to be stored onboard for different configurations based on the efficiency and maximum energy required between bunkering was calculated (Table 2). The weight and volume of storage tanks based on the specific storage capacity of different fuels were calculated. Similarly, the powertrain components for each configuration were sized based on the currently installed system and downstream efficiency, which is also shown in Table 2. The total volume and mass of the powertrain components for each configuration are calculated by adding the sizes of the powertrain components, fuel storage size, and the fuel itself (more detail in supplementary information Table S6).

Third, the feasibility of each configuration was checked based on the mechanical space available for each vessel, which varies among the different ships. For feasibility analysis, the mass constraint is assessed based on DWT, and the volume constraint is based on GT. A simplified method is used for assessing feasibility by comparing to the MGO option,
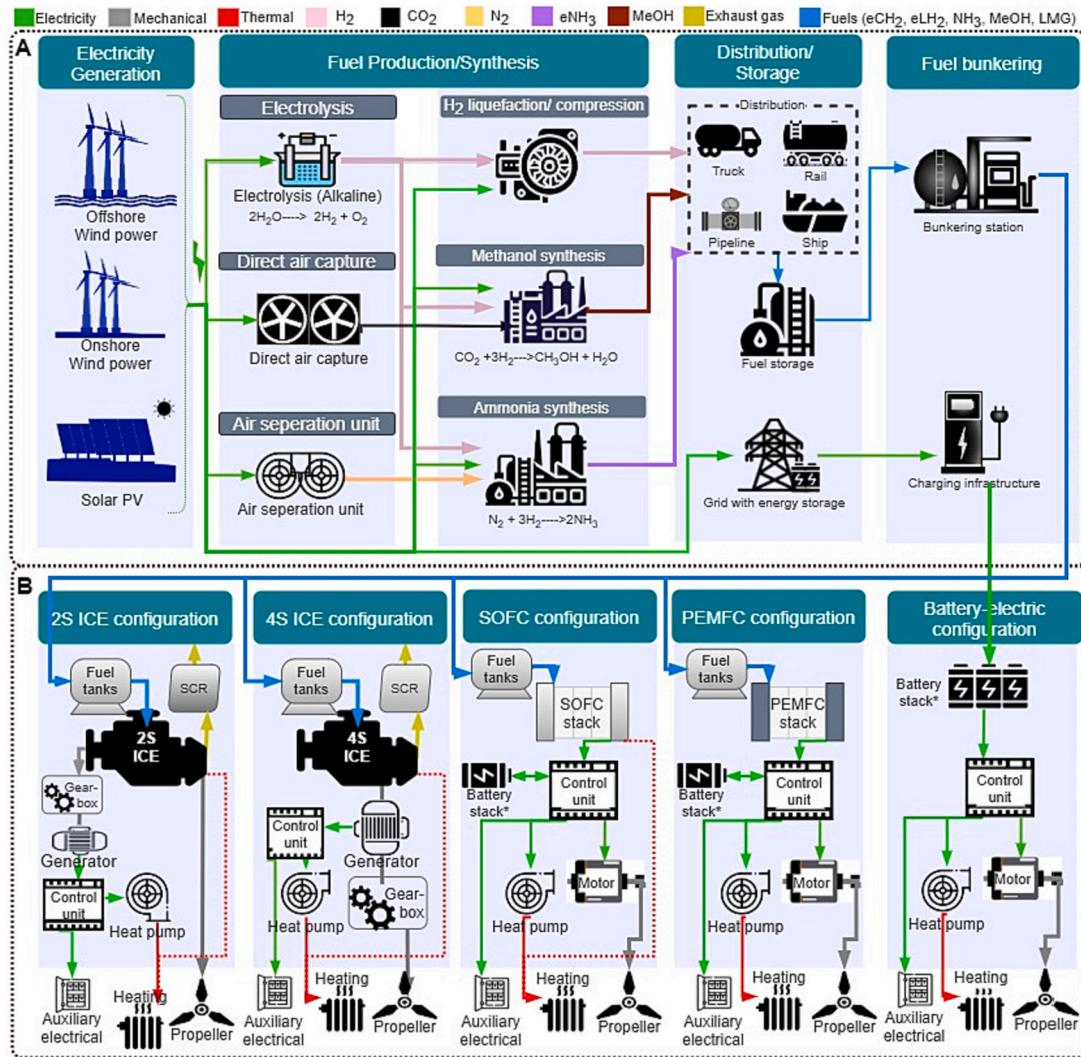
Fig. 1. A) Fuel production pathways considered in the study from well to tank. B) Propulsion system configuration considered in the study from tank to wake.

Table 2
The capacity of components for different configurations for each ship considered in the study.

	ICE configuration			PEMFC configuration			SOFC configuration			BE configuration		
	Tanker	Service vessel	RoPax vessel	Tanker	Service vessel	RoPax vessel	Tanker	Service vessel	RoPax vessel	Tanker	Service vessel	RoPax vessel
ICE/FC (kW)	7000	3520	23,040	6380	3240	21,450	6380	3240	21,450	0	0	0
Battery (kWh)	0	0	0	330	170	1200	1120	570	4000	8,359,870	58,670	48,8550
Fuel tank (GJ)	29,920	230	1900	28,870	200	1690	26,190	180	1530	0	0	0
Alternator (kW)	1285	960	2670	0	0	0	0	0	0	0	0	0
Electric motor (kW)	0	0	0	5880	2610	20,620	5880	2610	20,620	5880	2610	20,620
Heat pump (kW)	200	0	500	200	0	500	200	0	500	200	0	500

the ratio of total powertrain size including fuel storage to vessel size is calculated. For mass consideration, the ratio of propulsion machinery (including fuel storage and fuel) mass (PMM) to DWT is calculated (PMM/DWT) and for volume consideration, the ratio of propulsion machinery volume (PSV) including tank volume to GT is calculated. Design is considered infeasible if the ratios of decarbonization concepts are more than 3 times the mass ratio and 2 times the volume ratios for the MGO option for each ship type. The volume and mass constraints vary between ship types, for the tanker, similar to bulk

carriers the main constraint is on mass [19] whereas, for the RoPax and service vessel cases, the volume is critical.

In addition to the above method, the feasibility of the stability of the vessel with the new component and tank weights (both tank and fuel) and placement were analyzed with the help of concept-level designs that were also developed for case vessels, for propulsion systems using hydrogen and ammonia as fuel. The concept was developed only for the tanker and service vessel based on the vessels' stability booklet and operation to ensure that capsizing will not occur during the vessel's

various loading conditions. This concept-level design is not the focus of the study and is not done for the RoPax vessel case due to a lack of data. For an electric ship using battery power, the batteries do not, to the same extent, need to be arranged around the central shaft or fuel tanks [24]. Instead, the stability can, to some extent, be maintained by properly distributing the batteries throughout the interior of the vessel, hence a stability calculation was not done for electric vessel concepts. It may be noted that battery compartments also come with safety requirements that need to be taken care of. During detailed ship design, other factors such as the shape and size of the hull, the position of the center of gravity, and the distribution of other equipment and payload within the vessel should also be taken into account.

Another aspect of feasibility, regarding safety, involves ensuring that the hazards associated with the new fuels and systems are properly contained and managed. A workshop was held to identify high-level hazards through a structured group review of the functional areas shown in Fig. 2B: fuel storage system, fuel transfer system, fuel preparation space, and FC space. The battery system and FCs were assumed to have undergone marine class approval and were not included in the hazard identification study. 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 ammonia safety expert, naval architects familiar with the vessel operation, and study team members.

2.4. Life cycle assessment

The goal of the LCA is to investigate the environmental impact of the different decarbonization options assessed from cradle to grave. Since the life cycle evaluation is done for scenarios consisting of future technological systems, prospective LCA (pLCA) is used. In pLCA, systems are analyzed at a future time horizon (in this case ships built in the year 2030) when the systems are assumed to be matured. The pLCA and LCC methodologies used in the study are summarized in Table 3.

To conduct an inventory analysis, the processes within the system boundary are divided into the foreground and background processes, as shown in Fig. 2A. The foreground processes, the focus of the study, are modeled toward a future scenario (2030) where the technology is at a

Table 3
Summary of the pLCA and LCC methodology.

Functional unit	GT-km (RoPax vessel and service vessel) and DWT-km (tanker)	
Time horizon	2030	
Geographical boundaries	Components and ships are assumed to be produced in Europe. The fuel production facilities are assumed to be located near the port of operation.	
Cost flows	Cost in Euros (€) (with the base year 2021), considering the technical lifetime of the components and a yearly discount rate of 5%.	
System boundary / Life cycle phases	• Manufacturing phase (components in Fig. 1B) • Fuel production phase and distribution • Replacement phase (SCR/battery/FCs)	• Operation phase • End of life phase (components in Fig. 1B) • Ship structure
Impact categories	• Acidification • Climate change, (GWP20 and GWP100) • Ecotoxicity freshwater • Eutrophication marine • Eutrophication terrestrial • Eutrophication freshwater • Resource use, fossils	• Human toxicity, cancer effects • Human toxicity, non-cancer effects • Ozone depletion, • Particulate matter • Photochemical ozone formation • Land use • Resource use, minerals, and metals

commercial scale [12]. The predictive scenario method is used for upscaling emerging technologies in the foreground process to identify the parameters linked to energy, material, emission, infrastructure, and costs. Three predictive pathways: highly optimistic, optimistic, and pessimistic pathways are analyzed to select three different parameter values. The predictive scenario pathways are developed based on expert knowledge by interviewing experts (also called expert scenarios) [25]. Interviews were conducted with various experts from ten relevant fields for their opinion using a structured set of questions. The questions include the inventory collection over life-cycle phases in different time horizons based on their opinion on the likely development of the novel technologies. Parameters of pathways are also collected by comparing
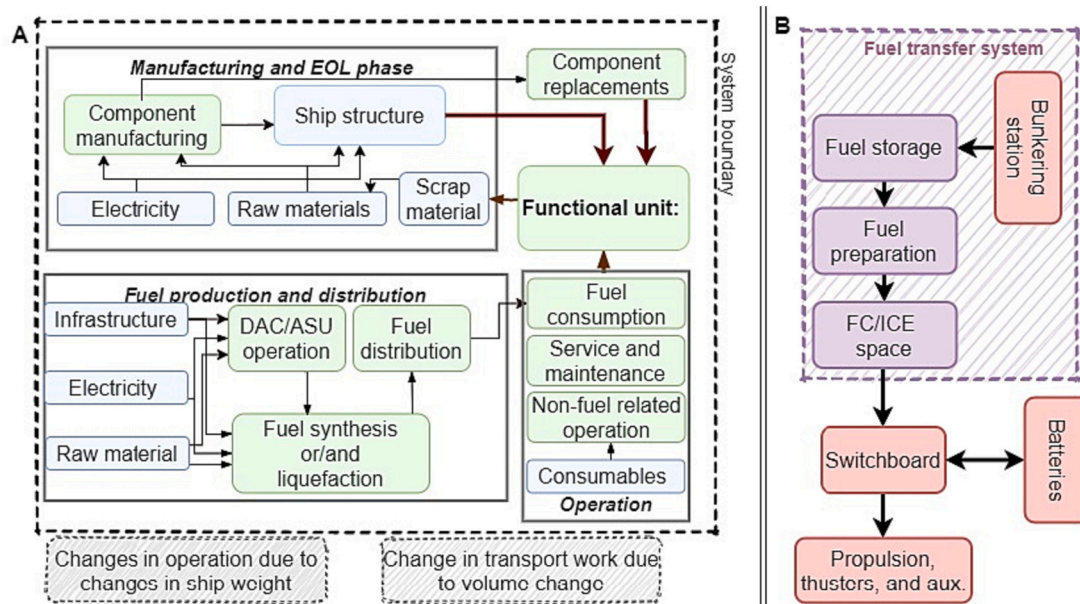
Fig. 2. A) System boundaries and processes considered in the LCA and LCC assessments, green colored boxes represent the foreground system and blue boxes represent the background system processes cost associated with ship structure is not included in the LCC. B)The main parts of the system that are relevant from a safety perspective, The system in focus for the safety workshop is marked in purple. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

different techno-economic and life cycle literature where some focus on the future situation. Parameters on the optimistic pathways are taken as inventory for the base calculation. Parameters in the highly optimistic and pessimistic pathways are used in the interpretation phase for uncertainty analysis (described in 2.7).

The background processes, on the other hand, are considered mature and static and are therefore not modeled in the study. Instead, they are adopted directly from secondary datasets such as Ecoinvent and Gabi, or literature. However, while choosing the parameters of the process based on existing data, temporal mismatch with the foreground system should be avoided [26]. In this study, temporal changes in the electricity mix of the grid are adjusted to the scenario projection for the year 2030 based on different forecasts by IEA [27]. The life cycle phases of the ship systems under study include fuel production, fuel distribution (together also called well-to-tank or WTT), operation (also called tank-to-wake or TTW), manufacturing, and end-of-life phases for the propulsion components, as well as shipbuilding and the replacement of propulsion components whose service life is shorter than the ship's lifespan.

The assessment is performed using the open-source program openLCA and a midpoint approach is used for the impact assessment in this study. For climate change, GWP20 and GWP100 are calculated based on the sixth assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) [28]. Besides climate impact which is in focus in this study (as well as in existing studies), the other thirteen impact categories in Table 3 are chosen and screened according to Environmental Footprint (EF) 3.0 methodology [29]. By including the majority of the impact categories proposed in that methodology, the potential impact on other environmental problems and shifts from one area into another one can be identified. Identifying such potential problems provide information that can be used to take necessary steps for avoiding them or to direct future research. The environmental impacts assessment (*IA*) for each category (*c*) is calculated from the environmental loads quantified in the inventory analysis phase using Eq. (1). Where CF_s is the characterization factor for substance (s) (based on the impact methodology selected) and mass of substance emitted (m_s).

$$IA_c = \sum_s CF_s \times m_s \tag{1}$$

The total life cycle impact assessment (LCIA) for each impact category is calculated by combining the environmental impact from fuel production (IA_{WTT} per MJ_{fuel}), operation (IA_{TTW} per kWh_{engine}), manufacturing with end-of-life recycling ($IA_{man,eol}$ per propulsion configuration), and replacement (IA_{repl} per component) phases as shown in Eq. (2). Manufacturing and replacement include end-of-life recycling by using the cutoff method, where a share of the secondary material is assumed in manufacturing (it avoids the burden of the primary production but includes the burdens caused by the recovery and upgrading processes [30]). In Eq. (2), f_c is annual fuel consumption, E_{op} is the ICE/FC output of propulsion system configuration (components in Fig. 1B) from the engine out to the propeller, *t* is the service life of the ship, and $N_{repl,i}$ is the number of replacements for component *i*.

$$LCIA_c = IA_{WTT,c} \times f_c + IA_{TTW,c} \times E_{op} + \frac{IA_{man,eol,c}}{t} + \frac{\sum N_{repl,i} \times IA_{repl,c}}{t} \tag{2}$$

Normalization: Normalization provides a reference situation for the environmental pressures to make relative environmental impact interpretation easier [31]. In this study, the global normalization factors (NFs) are taken from EF 3.0 based on the population [32].

2.5. Life cycle costing

LCC methodology is similar to LCAs but used for determining the economic performance of a product or system over its entire life cycle, including all the costs associated with the product or system, including capital, maintenance, repair, and disposal costs. LCC includes the cost flows in terms of expenses (outflow) and revenue (inflow) over different life cycle phases. A further aspect of LCC is that multiple stakeholders are involved in various life cycle phases, and each stakeholder has a different type of impact. The conventional LCC, used in this study is often from the perspective of a single actor, where discounting of the costs is also considered. In this study, the costs are calculated from the ship owners' perspective and the cost assessment is divided into two parts that are CAPEX-related costs and OPEX-related costs. The same scope and the functional unit of LCA are used in LCC to improve the comparability of studies. The CAPEX-related cost includes the capital cost for the acquisition of the propulsion system components, the capital cost for replacing the components, and the end-of-life cost. For cost comparison, the CAPEX-related costs are to be converted to the net present value (NPV) where the future cost is discounted to the present value using the capital recovery factor (*crf*) given in Eq. (3), where *t* is the service life of the ship, and *i* is the discounting rate (5%).

$$crf = \frac{i(1+i)^t}{(1+i)^t - 1} \tag{3}$$

CAPEX-related LCC is calculated using Eq. (4), where the first part represents acquisition cost, the second part represents replacement cost converted toward the functional unit ($€/kWh_{prop}$), and the end-of-life cost. *TEC* is the total equipment cost related to the acquisition of the propulsion system components, $R_{c,i}$ is the capital cost of the component (*i*) to be replaced, $M_{c,m}$ is the amount of metal m recycled in kg, and $C_{scrap,m}$ is the scrap value of the metal m

$$LCC_{CAPEX-related} = (TEC \times crf) + \sum (N_{repl,i} \times R_{c,i} \times crf) - (M_{c,m} \times C_{scrap,m}) \tag{4}$$

OPEX-related LCC includes fuel costs (main and pilot fuel), non-fuel costs (e.g., urea, lubrication oil), and external costs calculated using Eqs. (5) and (6), respectively. Fuel cost includes the cost associated with the consumption of main and pilot fuels, whereas non-fuel operation cost is associated with consumables like urea for SCR and lubrication oil, and maintenance cost. C_F is the cost of fuel in €/MJ, $C_{C,x}$ is the cost of the consumable in €/kg, $N_{c,x}$ is the annual amount of consumable (x), and C_M is the annual maintenance cost (€)

$$LCC_{\text{Fuel related OPEX}} = \sum C_F \times f_c \tag{5}$$

$$LCC_{Non-fuel\ related\ OPEX} = \sum C_{C,x} \times N_{c,x} + C_M \tag{6}$$

Total cost is the sum of $LCC_{CAPEX\text{-related}}$, $LCC_{\text{Fuel related OPEX}}$, and $LCC_{\text{Non-fuel related OPEX}}$ where all costs are adjusted to the functional unit. For comparing the cost associated with the GWP reduction potential, the carbon emission abatement cost (CAC) is calculated using Eq. (7) [33]. The CAC is an effective tool to compare the increase in the cost of technical options with the potential GHG reduction associated with the same technology.

$$CAC(€/tCO_2eq) = \frac{LCC\ relative\ to\ reference\ (€/kWhprop)}{GWP100\ relative\ to\ reference\ (tCO_2eq/kWhprop)} \tag{7}$$

2.6. Inventory data

Fuel production pathway and distribution: The data for the fuel production pathways (Fig. 1A) are based on [12]. However, in this study, the fuel production pathway for eCH2 considers compressed hydrogen storage at 700 bar (requiring a refueling pressure of 880 bar). The electricity required for compression is assumed to be 3.2 kWh/kg of hydrogen [34]. The parameters for fuel production pathways and fuel storage are summarized in Table 4. The dataset for the electricity from the wind power used in this study is from GaBi (details in supplementary information S2.1) (also in line with [80]). Table 4 also shows the costs used in the study which are calculated based on the assumptions in fuel production pathways detailed in [12]. In fuel distribution, temporary fuel storage would be required in the port to allow redundancy. As

Table 4

Technical and cost parameters for the fuel production pathways considered in the study. The inventory data for the infrastructures are adopted from the references mentioned in the last column.

	Cost parametersCAPEX	Cost parameters CAPEX	O&M cost[b] (% of CAPEX/year)		Infrastructure Ref
On-shore wind	41%[a]	1.04 M€/MW	4%	[35]	GaBi
Electrolysis	50 kWh/kgH$_2$	450 €/kW	5%	[36,37]	[36,38]
NH$_3$ synthesis	472 kWh/tNH$_3$	174 k€/tNH$_3$/day	5%	[37,39,40]	[41]
MeOH synthesis	858 kWh/tMeOH	69 k€/tMeOH/day	5%	[37,42,43]	[41]
H$_2$ liquefaction	7.0 kWh/kgH$_2$	2100 €/kgLH$_2$/day	4%	[44]	[44]
H$_2$ compression	3.5 kWh/kgH$_2$	2000 €/kgH$_2$/day	4%	[34]	[45]
ASU	314 kWh/tN$_2$	376 €/kgN$_2$/day	5%	[40]	[41]
DAC	875 kWh/tCO$_2$	271 €/kgCO$_2$/day	5%	[46,47]	[46]
Tank, MGO	0.02 m^3/GJ; 27.26 kg/GJ	0.02 (€/MJ)	2%	[18]	[12]
Tank, MeOH	0.07 m^3/GJ; 57.54 kg/GJ*	0.04 (€/MJ)	2%	[18]	[12]
Tank, NH$_3$	0.10 m^3/GJ; 68.64 kg/GJ*	0.08 (€/MJ)	2%	[18,48]	[12]
Tank, LH$_2$	0.16 m^3/GJ; 64.21 kg/GJ*	1.67 (€/MJ)	2%	[48,49]	[12]
Tank, CH$_2$	0.42 m^3/GJ; 190.57 kg/GJ*	5.00 (€/MJ)	2%	[49,50]	[49]

[a] Capacity factor.
[b] Including fixed O&M cost.
* Including the weight of fuel at maximum capacity.

detailed data on redundancy and capacity factor are not available, a storage capacity of three times the bunkering volume is assumed.

Since the environmental impacts are sensitive toward the electricity source [12], two scenarios are considered. In the first scenario, only electricity from wind power is assumed for fuel production. In the second scenario, a global build margin electricity (representing the additional electricity generation capacity expected built to meet the projected demand for electricity in the future) based on scenarios modeled by IEA [27] is considered (details in supplementary information Table S3). In pLCA, build margin electricity is typically used as a default assumption for the electricity mix that will be used to produce a product or service, because it represents the mix of electricity generation technologies that is most likely to be used in the future.

Propulsion system manufacturing, replacement, and EOL: The inventory

Table 5

The operational and cost assumptions of propulsion system components used in the study. For fuel tanks onboard, the same parameters as in Table 4 are used.

Component	Major parameter	Specific CAPEX cost	O&M cost (% of CAPEX/ year)	Refs	Material data
4SICE, Diesel	48% efficiency$_{me}$	240 €/kW	2%	[a], [18]	[53,54]
4SDF ICE*	48% efficiency$_{me}$	265 €/kW	2%	[a], [12]	[53,54]
2SICE, Diesel	50% efficiency$_{me}$	240 €/kW	2%	[a], [12]	[53,54]
2SDF ICE*	50% efficiency$_{me}$	265 €/kW	2%	[a] [12]	[53,54]
PEMFC	55% efficiency$_{el}$	1100 €/kW	0.5%	[a], [55]	[56]
SOFC	60% efficiency$_{el}$	2500 €/kW	0.2%	[a,] [12]	[57]
Electric motor	98% efficiency	120 €/kW	1%	[58,59]	[41]
Gearbox	98% efficiency	85 €/kW	1%	[12]	[54]
Alternator	97% efficiency	120 €/kW	1%	[59,60]	[61]
SCR system	NA	40 €/kW	2%	[22,62]	[63]
Battery	60% SOC	200 €/kWh		[9,64]	[65,66]
Heat pump	4 COP[b]	1000 €/kW	1%	[67,68]	[69]

[a] Based on expert interviews.
[b] Coefficient of performance; $_{me}$: *mechanical*; $_{el}$: *electrical*
* Lesser efficiency for eNH3ICEs due to high heat of vaporization is assumed (Table 6).

data for manufacturing and end-of-life of the components listed in Table 5 are also calculated using the same parameters as in [12]. FC stacks, batteries, and SCR are considered to be degraded at a higher rate than other components, hence these components need to be replaced based on their usage duration. The number of replacements is calculated based on the component life cycle and ship life cycle [51]. For FCs, the rate of degradation is assumed as 0.4% per 1000 h of operation, and it is assumed that when the ship is on the berth, the FCs won't be in operation. It is assumed that the FC will be replaced when it loses 20% capacity. For battery replacement a simple assumption of 15 years with a state of charge (SOC) of 60%. The simplified assumption is made because various characteristics that affect battery life are not known (e. g. the duration of usage, charging cycles, and battery charging technology) and these details would be known in the detailed design phase only. It is considered that the FC and battery-operated vessels will have less maintenance compared to ICE as there are few moving parts in these cases. Inventory details for raw materials used in the components are assumed from the Ecoinvent database. EU electricity mix as per the scenario projection for the year 2030 based on the European Commission 2020 reference scenario is assumed as input electricity in manufacturing processes [52].

Ship operation: The input flows and output flows depend on the combustion processes, emission factors of ICE/FC technology, efficiencies of the components, and additional load requirements for the operation of equipment (e.g. OCC). The exhaust emission and efficiency from the ICE depend on the operation load [13], and an ICE load of 80% is assumed during cruising and 20% when maneuvering. It is assumed that the ICEs/FCs won't be operated when the ship is at berth, and the electricity required will be supplied from the respective port. The inventory data of emissions from the combustion of fuel, specific fuel consumption, and urea consumption considered during the operation is summarized in Table 6. To use renewable electricity in ports additional onboard storage is required. A simplified assumption is that this storage can be met by the secondary use of batteries, and hence it is avoided in impact assessment. Other assumptions for efficiencies considered in the study are 98% for the control unit [54], charging efficiency of 86%, and battery discharge efficiency of 88%. During operation, the majority of emissions from ICEs are released in the form of exhaust gases [13], the main flows and parameters considered during the operation are shown in Table 6. Emissions to water and soil, such as bilge water and stern tube oil, are not considered in this study, as it is assumed that these emissions would be similar for all cases. It is also assumed that FC options have an electrochemical oxidation process.

Ship structure: The raw materials used in the ship structure are estimated based on the lightweight tonnage (LDT) of the selected ship. The

Table 6

Inventory data of emissions from the combustion of fuels in different technologies. ICE load of 80% for cruising and 20% for maneuvering are assumed. Emissions not listed are assumed zero. For NH_3 ICEs heating of vaporization about 1.4 MJ/kg is assumed which reduces the overall efficiency of ICE. Pilot fuel required is assumed to be 5% of energy content during cruising and 15% during maneuvering.

Technology used	2S, diesel cycle		2S, diesel cycle		2S, diesel cycle		2S, diesel cycle		SOFC	SOFC
Fuel used	NH_3		MeOH		H_2		MGO		NH_3	MeOH
LHV (g/MJ)	18.6		19.9		120		42.7		18.6	19.9
Pilot fuel	MGO		MGO		MGO		–	–		
ICE load	80%	20%	80%	20%	80%	20%	80%	20%	all loads	all loads
Fuel consumption (g/kWh)	397	411	344	356	57	59	169	195	320	301
Pilot fuel consumption (g/kWh)	8	29	8	29	8	29	–	–	–	–
Urea or *NH_3 for SCR (g/kWh)	5*	5*	10	10	10	10	10	10	–	–
Emissions (g/kWh) — CO_2	34	100	506	589	27	93	547	631	–	414
BC	0.0001	0.0004	0.0055	0.0096	0.0001	0.0004	0.0025	0.0025	–	–
CO	0.3	0.7	0.7	0.7	0.3	0.7	0.7	0.7	–	0.0091
N_2O	0.1	0.1	0.003	0.003	0.02	0.02	0.03	0.03	–	–
CH_4	0.001	0.002	0.01	0.01	0.001	0.002	0.01	0.01	–	–
NOx	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	0.0031	0.0008
PM_{10}	0.01	0.03	0.01	0.03	0.04	0.04	0.10	0.10	–	0.0001
SOx	0.016	0.057	0.016	0.057	0.016	0.057	0.330	0.381	–	–
NH_3	0.05	0.05	0.05	0.05	0.05		0.05	0.05	–	–
Formaldehyde	–	–	–	–			–	–	–	–

Technology used	Dual fuel, 4S Otto		Dual fuel, 4S Otto		Dual fuel, 4S Otto		4S, diesel cycle		PEMFC
Fuel used	H_2		NH_3		*MeOH*		*MGO*		H_2
LHV (g/MJ)	120		18.6		19.9		42.7		120
Pilot fuel	MGO		MGO		MGO		–		–
ICE load	80%	20%	80%	20%	all loads	20%	80%	20%	all loads
Fuel consumption (g/kWh)	59	61	414	429	358	370	176	203	55
Pilot fuel consumption (g/kWh)	9	30	9	30	9	30	–	–	–
Urea or *NH_3 for SCR (g/kWh)			5*	5*	3	4	9	9	–
Emissions (g/kWh) — CO_2	28	97	28	97	520	606	568	645	–
BC	0.0003	0.0008	0.0003	0.0008	0.0016	0.0033	0.005	0.005	–
CO	0.3	0.7	0.3	0.7	0.1.7	2.2	1	1	–
N_2O	0.02	0.02	0.1	0.1	0.003	0.003	0.03	0.03	–
CH_4	0.001	0.002	0.001	0.002	0.01	0.01	0.01	0.01	–
NOx	0.7	0.7	2.6	2.6	2.6	2.6	2.6	2.6	–
PM_{10}	0.01	0.03	0.01	0.03	0.093	0.093	0.4	0.5	–
SOx	0.017	0.060	0.017	0.060	0.017	0.060	0.343	0.397	–
NH_3	–	–	0.05	0.05	0.025	0.025	0.05	0.05	–
Formaldehyde	–	–	–	–	0.00049	0.00049	–	–	–

percentage compositions of raw materials are adopted from Jain et al. [70].

2.7. Interpretation of result

As the technologies are in the early stages of development, the parameters used in the study may alter as the technologies develop further. GHG intensity of the electricity mix is one of the factors that determine the reduction potential of the e-fuels [12]. A scenario analysis is performed with two electricity mixes, in scenario one, the electricity in the fuel production is considered from wind power, and in Scenario 2, the estimated global build margin is assumed from the forecast done by the IEA energy outlook [27]. In addition, since most of the technologies evaluated are still in the early stages of development, their performance may change as they mature. To account for this possibility, an uncertainty analysis using Monte-Carlo simulation was conducted to assess the impact of these potential changes on the results. The following aspects were tested for their influence on the total environmental impact for each assessed option and each vessel: the effect of electricity production using scenario analysis, leakages in the fuel supply chain, the efficiencies of energy conversion, the energy required during fuel production, and the possible N_2O emissions from NH_3 based ICEs. A similar uncertainty analysis was also conducted for the LCC results. The ranges of alternate parameters used in the analysis are shown in Table 7. For the uncertainty analysis, the simulations were iterated 10,000 times using a uniform distribution of the range of parameters, for both the life cycle inventory and cost flows.

3. Technical viability

The volume and mass feasibility of the different concepts using the method described in Section 2.1 is shown in Fig. 3. Compressed hydrogen is not feasible for the tanker and the RoPax vessel due to the lower energy density of the energy carrier and high energy consumption between bunkering. The BE option is not feasible for all ship types due to low gravimetric energy density. The mass constraint is more critical for tankers than service and RoPax vessels, hence the possibility of using the battery option for service RoPax vessels cannot be completely ruled out and is hence taken for further analysis (shown in blue colour). This is similar to the volume constraint of the tanker, since there is space available on the deck the options with high volume cannot be ruled out (shown in blue colour).

Fig. 4A shows conceptual ship designs for H_2 PEMFC system for the service vessel for supplying the ship with power. The figure also shows the volume constraint for this ship type as storage onboard is difficult as it hinders the movement of the cranes and placing deck cargo. Cargo is loaded both on the deck and on the main deck above the cargo room. Whereas in Fig. 4B fuel where the tanks are placed on deck, the concept design also avoids conflict with cargo tanks and the operation. Even with tanks onboard for LH_2 and NH_3 the intact stability of the ship is within an acceptable range for all loading conditions.

Regarding safety, all concepts are considered feasible but many 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 hydrogen, and requirements for ensuring no NH_3 gas release through scrubbing of vent gases are necessary according to the current

Table 7

Parameters varied for the scenario and uncertainty analysis. For the uncertainty analysis for the LCA and LCC, the range and the base case value are presented.

Description of parameter	Parameter ranges or scenario
Scenario analysis (LCA)	
GHG intensity of electricity for fuel production	Scenario 1: electricity assumed from wind power
	Scenario 2: electricity assumed as global build margin between 2030 & 2050
Uncertainty analysis (LCA)	
Leakages for the liquefied gaseous fuel during distribution and bunkering.	CH_2: min: 0.75%, base case: 1.5% [48], max: 3%
	LH_2: min: 0.75%, base case: 1.5% [48], max: 3%
	NH_3: min: 0.05%, base case: 0.1% [48], max: 0.2%
Efficiency of ICE/FCs and battery energy storage capacity.	*ICEs: ±5%; PEMFCs: ±5%; SOFCs: ±5%*
	Battery capacity (Wh/kg) (case 9): min: 180, max: 240
Energy use linked to fuel production.	*Electrolysis (kWh/kg$_{H2}$): min: 53, max: 47*
	eH$_2$ liquefaction (kWh/kg$_{H2}$): min: 6, max: 8
	eNH$_3$ synthesis (kWh/kg$_{NH3}$): min: 0.333, max: 0.874
	eMeOH synthesis(kWh/kg$_{MeOH}$): min: 0.437, max: 1.292
	DAC (kWh/kg$_{CO2}$): min: 0.600, max: 1.230
N_2O emission for eNH3ICEs (g per kWh')	*Min: 0.03; max: 0.30*
Uncertainty analysis (LCC)	
Fuel costs (€/GJ)	eNH$_3$ cost: high: 36.71, base: 32.14, low: 27.47
	eMeOH cost: high: 41.91, base: 37.18, low: 32.39
	eCH$_2$ cost: high: 33.05, base: 28.95, low: 24.72
	eLH$_2$ cost: high: 34.83, base: 30.66, low: 26.49
	Electricity cost: high: 19.44, base: 13.89, low: 8.33
	MGO cost: high: 18.74, base: 16.39, low: 12.88
Capital cost of equipment	PEMFC: 800 to 1200 €/kW
	SOFC: 2000 to 3000 €/kW
	Batteries: 100 to 250 €/kWh

guidelines. A comprehensive risk assessment of a detailed design must be completed as part of the approval process for the alternative design. For the safety of crew members in the event of NH$_3$ leakage, personal protective equipment should be available onboard and worn as required when working with or near ammonia systems. For passenger vessels using NH$_3$, extra protective measures would be required for the passengers as well, but have not yet been defined in regulations [71].

4. Life cycle results

4.1. Climate change impact

The GWP100 results for both scenarios, (scenario 1: assuming wind power for fuel production and scenario 2: assuming global build margin for fuel production), for all three vessels, are shown in Fig. 5. Only decarbonization options that were found technically feasible are shown in life cycle results. In the first scenario, all feasible options could reduce climate impact significantly compared to the reference case with MGO (80–90% GHG reduction potential). There is a notable change in the GWP100 results for the second scenario, but there is still a significant GHG reduction potential (67% to 85% GHG reduction potential).

In the first scenario, results show that eLH2PEMFC has the highest GHG reduction potential for both the RoPax and service vessel cases. For the service vessel, the eCH2PEMFC has the second highest potential. Even though the fuel production stage has a low impact for compressed hydrogen than eLH2 options, the requirement of larger tanks onboard and at port counterbalances the downstream benefit. eCH2 options were found not feasible for the other ship cases. eNH3SOFC was found to have the highest reduction potential for the tanker and the second highest reduction potential for the RoPax vessel. eMeOHSOFC has the second-highest reduction potential for the tanker. For the RoPax vessel, the feasibility of the eNH3SOFC and eNH3ICE options in terms of the safety risk for the passengers onboard is a concern as mentioned in Section 3.

In the second scenario, for the RoPax vessel, BE has the highest reduction potential followed by eNH3SOFC. The difference between scenarios is due to lifecycle energy conversion efficiency versus the GHG impact of the electricity. The BE option has high overall efficiency and thus less electricity is required in the total life cycle. In the second scenario, the impact from the manufacturing of the battery (which includes the need for a replacement of batteries due to the shorter lifetime of batteries than the lifetime of the ship) is compensated by the higher efficiency as less electricity is used. Whereas in scenario 1, when electricity carbon intensity is less there is no potential advantage from higher efficiency on GWP. For the tanker, the order of the GWP reduction potential is similar to scenario 1. For the service vessel, there is a notable climate impact for batteries due to the low energy use in the operation as the ship is mostly idle in the port resulting in low utilization of the installed battery capacity during the operation life. This shows that BE options will have climate benefits not only depending on battery size but also on how effectively batteries are used.

For specific fuels, FCs have a lower climate impact than ICEs which is primarily due to the combustion of fossil-based pilot fuel in ICEs. Moreover, FCs have cleaner electrochemical combustion and higher efficiencies. The climate impact from the higher material demand for FCs (compared to ICEs) was compensated by the higher efficiency and cleaner combustion. Since the ship structure is assumed the same for each vessel irrespective of the decarbonization pathway, the impact from the ship structure only vary between ships, and its share of the GWP impact is different for different ship based on the utilization rate of

		eNH3ICE	eNH3SOFC	eMeOHICE	eMeOHSOFC	eCH2ICE	eLH2ICE	eCH2PEMFC	eLH2PEMFC	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%

Fig. 3. Feasibility of different concepts for different ship types. Green represents a high feasibility option and orange represents an infeasible option. Yellow represents a higher risk in terms of safety but is still feasible. Blue represents not feasible as per the cut-off criteria, but as argued in the text the size parameter may not be critical for the BE option for these ship types.
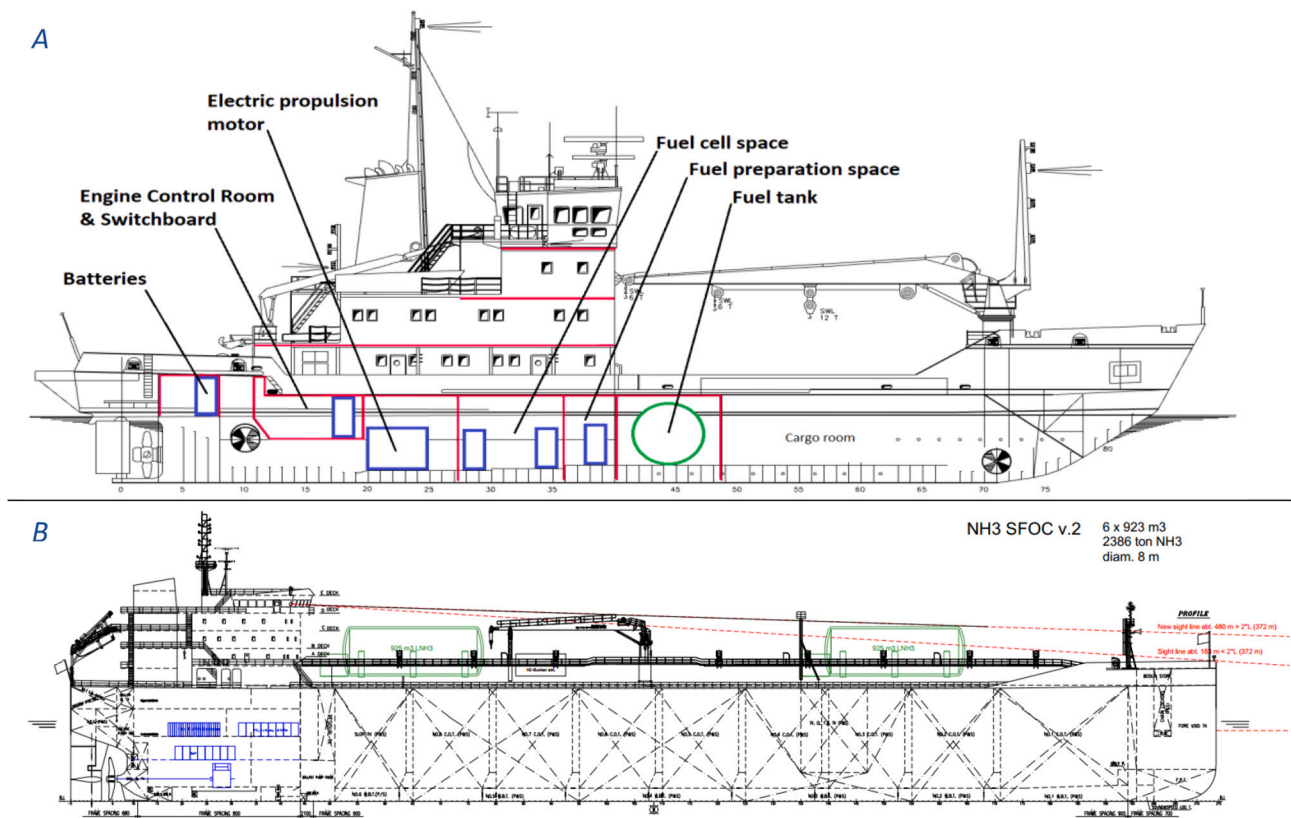
Fig. 4. A) Conceptual general arrangement drawing of the service vessel showing energy storage and main propulsion system components for the eLH2PEMFC concept. B) General arrangement drawing of the tanker with components for the eNH3SOFC concept. NH$_3$ tanks are shown in green and FCs, propulsion motor, batteries, and switchboard components are in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the ship.

The results of the Monte-Carlo simulation, based on the range of parameters, are also shown in Fig. 5 as uncertainty bars. The uncertainty is very low for all FC options, as the impact difference is only associated with downstream processes. However, the uncertainties are high for ICE options, as the impact can change both upstream and downstream. For eNH3ICE, the high uncertainty values are due to the significant differences in N$_2$O emissions (which is a strong GHG) used in the uncertainty analysis. The N$_2$O emission is a major challenge for NH3ICEs due to the presence of the nitrogen atom in the NH$_3$. The amount of these emissions is still uncertain as the technology is immature and hence it is critical for NH$_3$-fueled ICE systems to control the N$_2$O emissions to have climate impact reduction benefits. For MGO cases, GWP uncertainty is high as MGO has the highest emissions during well-to-propeller it is also mostly affected by assuming an equal uncertainty in engine efficiency between ICE options.

The analysis indicates that there is no significant difference in the results when using different functional units for the same case ship; the choice of the functional unit would affect the results when applied to different ships due to variations in ship lifespan, component utilization, and other factors. As the function performed by each case study ship is different, comparing the LCA results between the case ships would be an inappropriate comparison. It is primarily the results for the different fuel and propulsion options for each case study vessel that should be compared and not between the different ship cases. Higher efficiencies result in less fuel being combusted and thereby reduced the emission of carbon into the atmosphere. Thus, for ICEs, the choice of engine type i. e., 2S and 4S is also important.

4.2. Other environmental impacts

Fig. 6 and Fig. 7 show an overview of how the investigated fuel and propulsion options perform for the other included environmental impact categories. Figs. 6a to 6c present the normalized value of other environmental impacts for RoPax vessel, tanker, and service vessel respectively. Fig. 7 indicates the difference within each environmental impact category compared to MGO (decrease or increase). The detailed result for each environmental impact for scenario 1 and scenario 2 is shown in the supplementary information section 3. The result shows that the assessed decarbonization options also significantly reduce impacts like acidification, ecotoxicity, eutrophication (except for NH$_3$ options), ionizing radiation, land use, ozone depletion, particulate matter, photochemical ozone formation, and resource use (fossil). The reduction of acidification is primarily because the e-fuels produced from the electricity have no sulfur content. For the ICEs, acidification stands out from FCs due to the use of pilot fuel containing sulfur and also due to the emission of nitrogen oxides. A similar trend can be observed for photochemical ozone formation, particulate matter, and terrestrial eutrophication.

It can be noticed that the use of NH$_3$ in ICEs has a relatively higher contribution to impact categories such as marine eutrophication and terrestrial eutrophication. These impacts are mainly linked to the leakage of the NH$_3$ in the supply chain and also the emission of nitrogen oxides from the ICEs. Such impacts can be critical in sensitive areas such as the Baltic Sea and North Sea ECAs. The potential use of SCRs with appropriate catalysts and operating parameters can utilize the unburned NH$_3$ slipped from the ICE to reduce NOx and N$_2$O emissions, although currently there is a lack of data on this possibility. For SOFC, since it is assumed that the energy is converted using cleaner electro-chemical combustion, and the above-mentioned impacts are reduced as
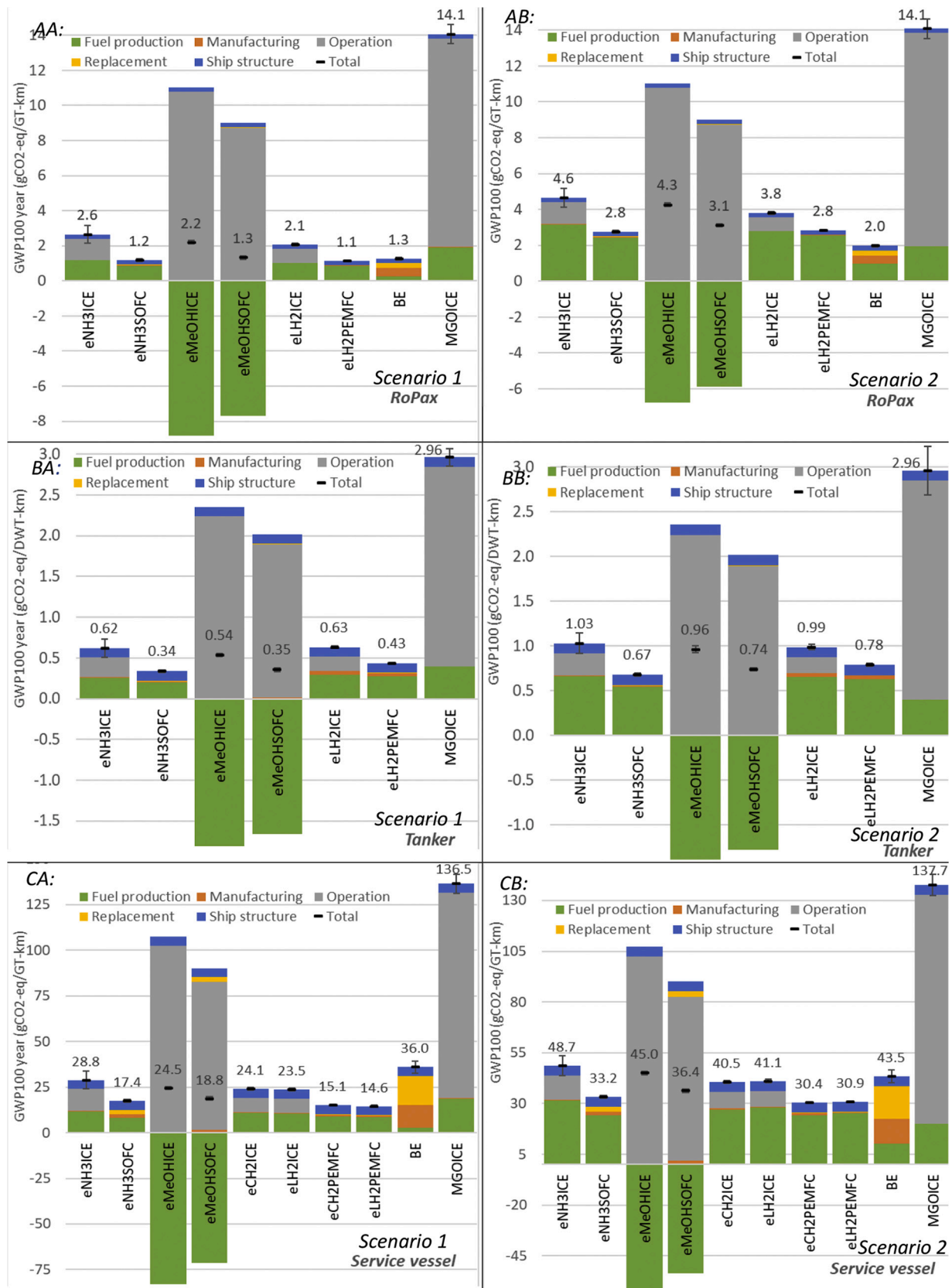
Fig. 5. GWP100 overview of both scenarios (In Scenario 1, the energy carrier is produced using electricity from the wind power whereas, scenario 2 assumes electricity as the global build margin) for the assessed options for different (left column shows scenario 1 and right column show scenario. AA) GWP100 for RoPax in scenario 1, AB) GWP100 for RoPax in scenario 2, BA) GWP100 for tanker in scenario 1, BB) GWP100 for tanker in scenario 2, CA) GWP100 for service vessel in scenario 1, and CB) GWP100 for service vessel in scenario 2.
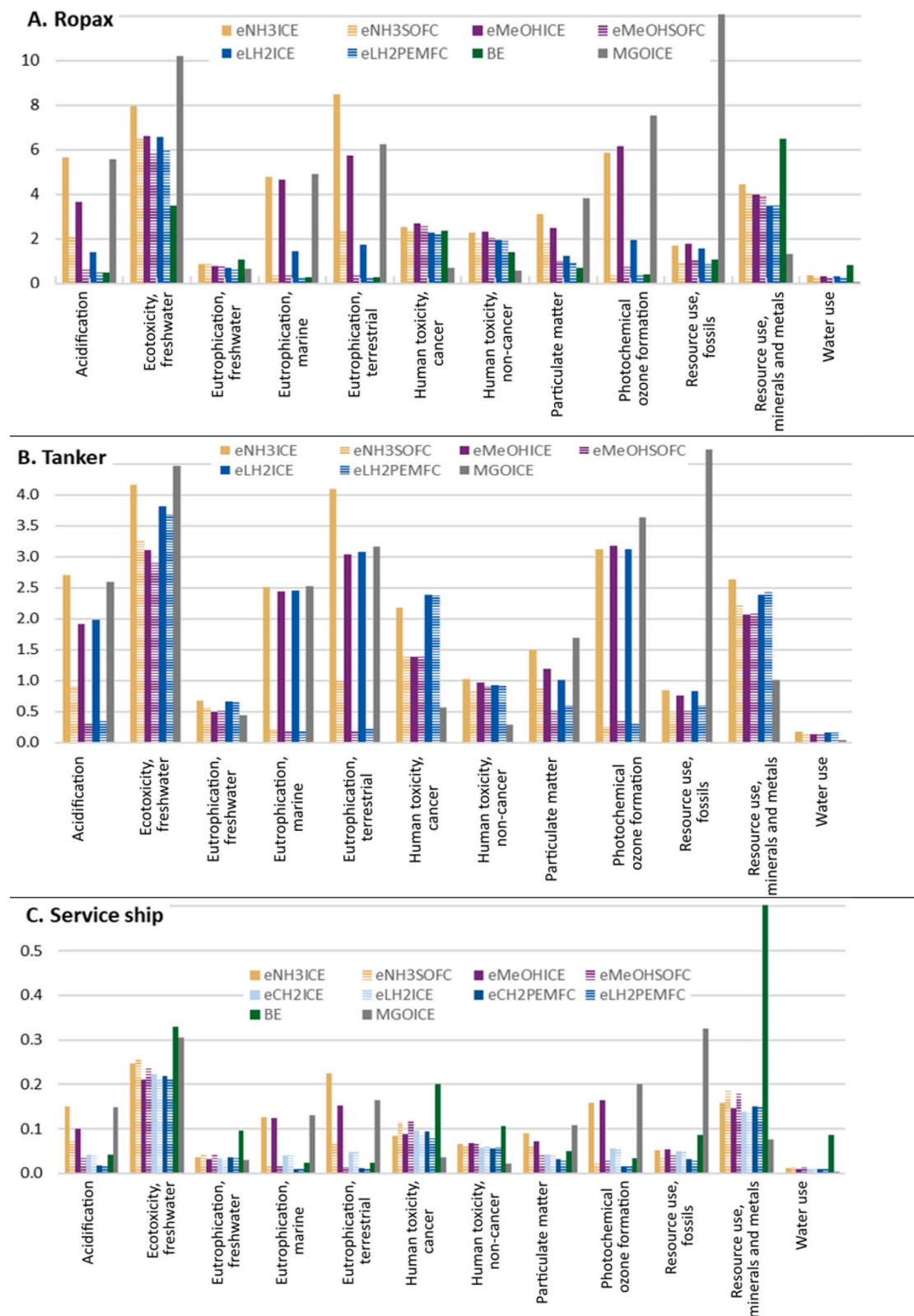
Fig. 6. Overview of the environmental impacts for the assessed options for different ships, results normalized with EF3.0 global normalization factor for A) RoPax vessel, B) tanker, and C) service vessel, Impact categories Ionizing radiation, land use, and ozone depletion is not shown as the normalized values are close to zero (for details refer to supplementary information).

	eNH3ICE			eNH3SOFC			eMeOHICE			eMeOHSOFC			eCH2ICE	eLH2ICE			eCH2PEMFC	eLH2PEMFC			BE	
	Ropax	Tanker	Service ship	Ropax	Tanker	Service ship	Ropax	Tanker	Service ship	Ropax	Tanker	Service ship	Service ship	Ropax	Tanker	Service ship	Service ship	Ropax	Tanker	Service ship	Ropax	Service ship
Acidification	1	1	1	0.4	0.3	0.5	0.7	0.7	0.7	0.1	0.1	0.3	0.3	0.3	0.8	0.3	0.1	0.1	0.1	0.1	0.1	0.3
Ecotoxicity, freshwater	0.8	0.9	0.8	0.6	0.7	0.8	0.6	0.7	0.7	0.6	0.6	0.8	0.7	0.6	0.9	0.7	0.7	0.6	0.8	0.7	0.3	1.1
Eutrophication, freshwater	1.3	1.5	1.2	1.3	1.2	1.5	1.2	1.1	1.1	1.2	1.2	1.5	1.1	1.1	1.5	1.1	1.2	1.1	1.5	1.2	1.6	3.3
Eutrophication, marine	1	1	1	0.1	0.1	0.1	0.9	1	1	0.1	0.1	0.1	0.3	0.3	1	0.3	0.1	0.1	0.1	0.1	0.1	0.2
Eutrophication, terrestrial	1.4	1.3	1.4	0.4	0.3	0.4	0.9	1	0.9	0.1	0.1	0.1	0.3	0.3	1	0.3	0.1	0	0.1	0.1	0	0.1
Human toxicity, cancer	3.5	3.9	2.4	3.4	2.5	3.2	3.8	2.5	2.5	3.8	2.5	3.4	2.7	3.2	4.3	2.3	2.6	3.1	4.2	2.3	3.3	5.6
Human toxicity, non-cancer	4	3.6	3	3.3	2.9	2.7	4	3.4	3	3.6	3.1	2.9	2.6	3.4	3.3	2.7	2.5	3.3	3.2	2.6	2.5	4.7
Ionising radiation	0.1	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.8
Land use	0.2	0.3	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.1	0.1	0.2	0.1	0.2	0.9
Ozone depletion	0.1	0.1	0.1	0	0	0	0.1	0.1	0.1	0	0	0	0.1	0.1	0.1	0.1	0.1	0	0	0.1	0	0.1
Particulate matter	0.8	0.9	0.8	0.5	0.5	0.6	0.7	0.7	0.7	0.3	0.3	0.4	0.4	0.3	0.6	0.4	0.3	0.2	0.4	0.3	0.2	0.5
Photochemical ozone formation	0.8	0.9	0.8	0.1	0.1	0.1	0.8	0.9	0.8	0.1	0.1	0.1	0.3	0.3	0.9	0.3	0.1	0.1	0.1	0.1	0.1	0.2
Resource use, fossils	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.3
Resource use, minerals and metals	3.3	2.6	2.1	3.1	2.2	2.4	3	2	1.9	2.9	2.1	2.3	1.8	2.6	2.4	1.8	2	2.7	2.4	1.9	4.9	7.9
Water use	6.1	4.1	3.8	5.5	3.7	5	5	3.2	3.2	4.9	3.3	4.7	3.4	5.2	3.8	3.4	3.3	5.1	3.7	3.3	13	30
IPCC 2021 GWP 100	0.2	0.2	0.2	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.3
IPCC 2021 GWP 20	0.2	0.2	0.2	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.3

Fig. 7. Overview of all environmental impact normalized to the reference case MGO, where the MGO value for all categories is one.

compared to the ICE option.

Some of the environmental impact categories show higher impacts compared to MGO, which include human toxicity (cancer, non-cancer), water use, and resource use (minerals and metals). The increase in human toxicity is largely caused by the electricity produced by wind power and requires attention. Possible formaldehyde emissions from MeOHICEs due to incomplete combustion also contribute to human toxicity. The use of an exhaust after-treatment system with suitable catalysts may be able to control formaldehyde emissions from eMeOH-fueled ICEs. Resource use, including minerals and materials, is also a bottleneck for these assessed technologies, particularly for electrolyzers used in hydrogen production, FCs, wind power, and batteries used in vessels. BE option has high resource use and water use mainly associated with the production of battery cells. Another factor to consider is water use, as it is the main feedstock for electrolysis. When choosing a fuel production site, it is important to evaluate the availability of water resources and how they may impact other sectors.

4.3. Life cycle costing

LCA results showed that there was no difference in the relative effect between options when using different functional units for the same case ship, hence LCC result was shown only for one functional unit (annual cost), the LCC cost for the other functional unit is shown in SI section 3. Fig. 8 shows the LCC results along with CAC and uncertainty analysis for all three case study ships. Among decarbonization options for all case ships, eNH$_3$ 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. Fuel cost makes up the largest part of total cost except for the BE option, where the cost of the battery has the highest share. Distribution cost is high for the hydrogen option and BE as the infrastructure for the bunkering is complex for these energy carriers. Comparing the results of the different ship cases shows that, depending on parameters like installed capacity and amount of energy required for the operation, the cost difference between decarbonization options varies significantly. Despite lower fuel consumption compared to ICEs, FC options tend to have relatively high costs for all ship types.

CAC results also show the same trend, that is NH$_3$ and MeOH fuel used in ICEs have a lower cost than other options. This also varies widely with ship types. CAC ranges from 240 €/tCO$_2$ to 400 €/tCO$_2$ for the RoPax vessel, 250 €/tCO$_2$ to 600 €/tCO$_2$ for the tanker, 250 €/tCO$_2$ to 2000 €/tCO$_2$ for the service vessel.

The LCC cost of the BE option is relatively close to the MeOH and NH$_3$ in ICE options, for the RoPax vessel, this is primarily due to the reduced higher life cycle efficiency in BE pathway which compensates for the high capital cost (manufacturing and replacement). The RoPax vessel has the highest annual energy consumption of all options, hence life cycle energy efficiency gives more benefit in reducing the overall cost. However, FCs options have a higher LCC as efficiency improvement didn't compensate for the capital cost.

The MeOH and NH$_3$ options in ICEs have a clear cost advantage over other options for the tanker. This is due to not only the lower capital costs of ICEs compared to FCs, but also the higher efficiency of 2S ICE in tankers, which operate mostly in cruising mode on the high seas. In contrast, the eLH$_2$ option is costly due to not only the price of hydrogen distribution but also the need for larger storage tanks.

For the service vessel, it is the capital cost of components that has a larger role in the total cost than the fuel. This gives a clear advantage for all ICE options including liquid hydrogen. FCs and BE options are significantly more expensive. This is primarily because the ship spends most of its time in docks and consumes less energy annually for operation.

4.3.1. Robustness of result

For the RoPax ship case (Fig. 8), the uncertainty results indicate that the total costs for all options overlap, indicating that all technologies are competitive For the tanker and service vessel cases there is a significant difference between options except for eNH3ICE and MeOHICE, and final feasibility would be based on detailed design including factors like safety, fuel availability, etc. Large variations can also be seen in CAC, which is mainly linked with efficiency. Higher efficiency of ICEs/FCs reduces direct emission of GHG from the operation as well as reduces emission from fuel production because less fuel needs to be produced. The higher emission also reduces the cost of operation because less fuel is required. So higher efficiency reduces the total GHG emissions and also the total cost.

The total cost is sensitive to the fuel costs and fuel cost depends primarily on the electricity cost. Fig. 9 shows the cost sensitivity of the
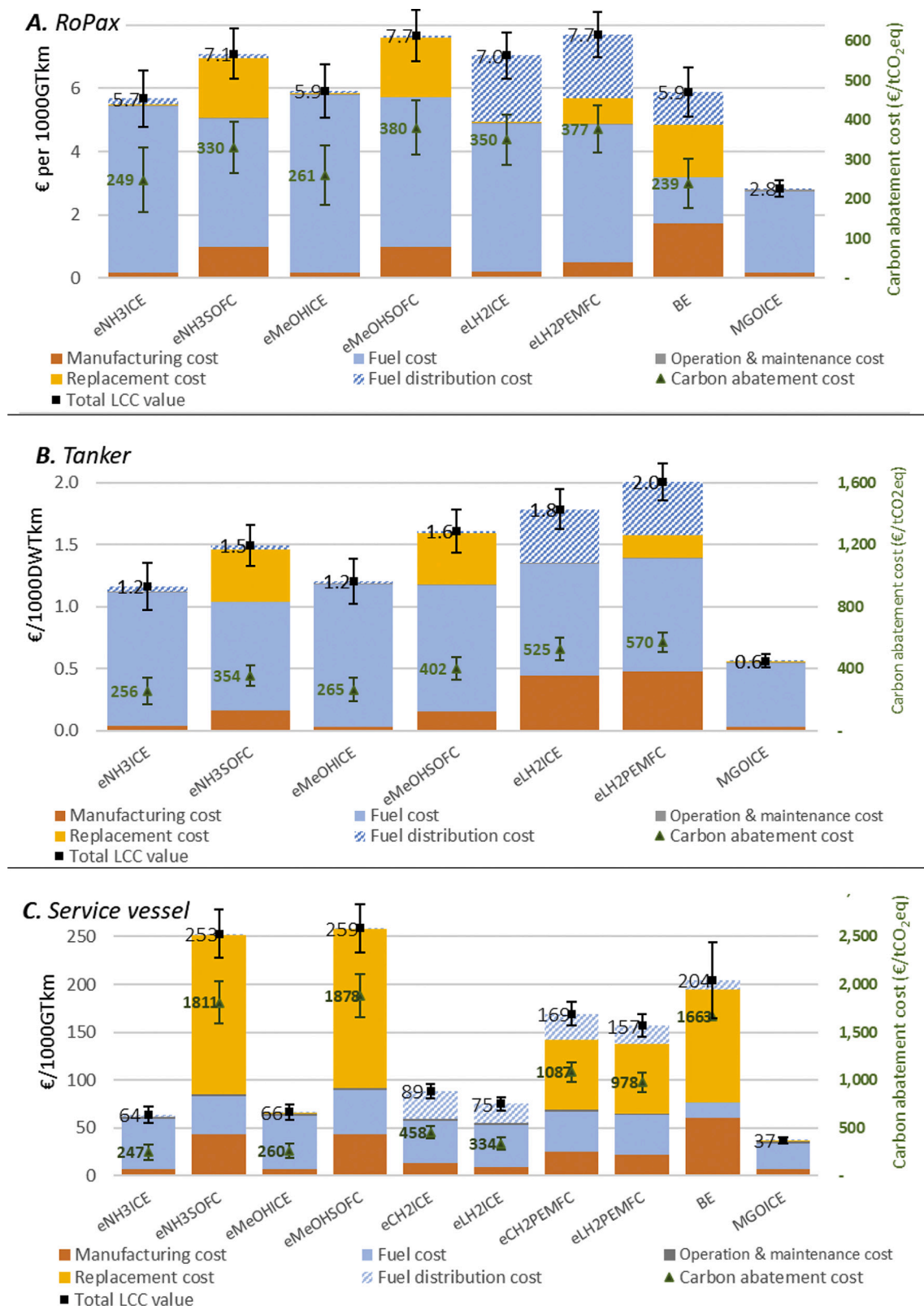
Fig. 8. Economic assessment of studied options over the entire life cycle for the three case study ships, A) RoPax vessel, B) tanker, and C) service vessel. The figure includes the annual LCC cost, carbon abatement cost, and uncertainty analysis. The bars represent only the mean value of the costs associated with different phases. The carbon abatement cost is represented by green triangles and values should be read from the secondary y-axis (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
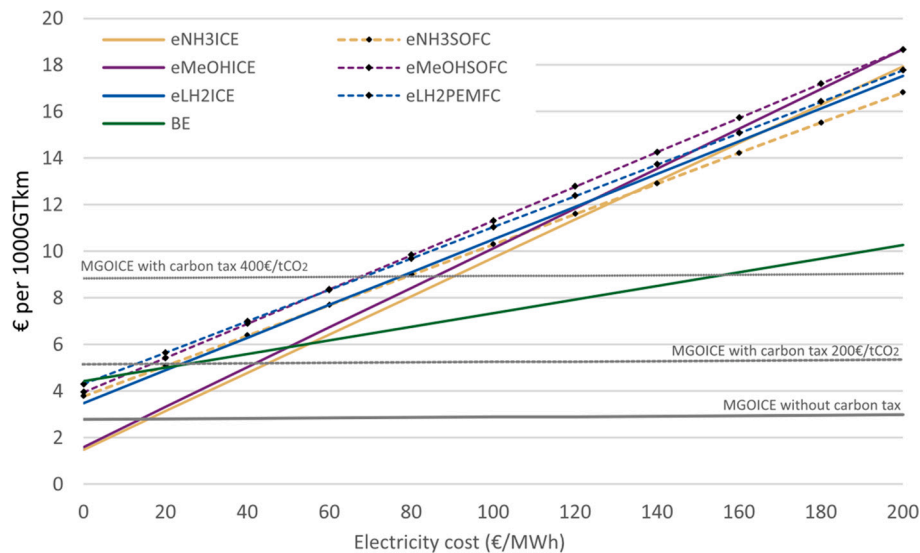
Fig. 9. LCC for different pathways for RoPax vessel considered in relation with the electricity cost and the effect of carbon tax for MGO ICE.

different options for RoPax. If electricity cost is high, more energy-efficient pathways like BE and FCs would have an advantage. As another example, if all base cost remains the same, eNH$_3$ in SOFC become more competitive than eNH$_3$ in ICE. Fig. 9 also shows how different levels of a carbon tax can make the options more economically feasible. At carbon taxes above 400€/tCO$_2$ and electricity prices below 70€/MWh most of the scenarios have lower costs than fossil-based MGOICE. The sensitivity analysis of cost for the tanker and service vessel is in the supplementary information.

5. Discussion

The study assessed the technical feasibility, environmental impact, and cost of different renewable energy carriers (electricity and e-fuels).

5.1. Technical feasibility

An examination of the volume and mass of compressed hydrogen based on a feasibility analysis reveals its low suitability for the case study ships and similar vessels. This is due to low volumetric efficiency and the need for a larger number of energy storage tanks onboard, which would increase the ship's weight. In this analysis, it was found that eCH$_2$ was only feasible for the service vessel that also was close to the boundary of the feasibility criteria. Based on this analysis, it can be argued that it is not only the distance that determines the feasibility of different options but also the speed, size, and operation profile that determines the energy consumption. For example, for the RoPax vessel analyzed, despite the shorter route distance the fuel consumption is high due to speed and size. Similar to eCH$_2$, the BE ships are not suitable when the energy consumption between bunkering operations is high.

A simplified feasibility assessment is done in this study, so if an option is found feasible for a given ship with this method, this does not imply that it is necessarily feasible to retrofit that specific ship. That is, significant changes would be required in the placing and arrangement of machinery inside the ship. A similar feasibility approach is done in other studies based on the size as a critical parameter for assessing feasibility, for example, the feasibility of batteries in container shipping by assessing volume [24], the feasibility of different energy carriers for bulk carriers by assessing mass [19], and the feasibility of energy carriers for different ship types was assessed based on mass and volume on a fleet [72].

5.2. Environmental impact from a life cycle perspective

Regarding the LCA result, GHG reduction potential and life cycle cost of different e-fuels vary with the ship types making it evident that the decarbonization strategies should be different for different ship types and operation profiles. For a summary see the Discussion section. Few studies have included the impact of components and infrastructure in LCA for e-fuels in the shipping sector. Regarding LCA, the results of this study are similar to the previous study [12], showing high GWP reduction potential for FC options. Spark-ignited ICEs were assumed in [12] while 4S dual-fuel ICEs were considered in this study.

When comparing the results from this study to the results presented in [12], some differences can be noted. In [12] the impact on fuel production was high as the ICE efficiencies were lower, and no pilot fuel was assumed, whereas in this study pilot fuel MGO is considered and fossil-based CO$_2$ emission from the pilot fuel shows a higher impact in the operational phase but a lower impact in the fuel production phase. Compared to [12], this study assumes a lower carbon intensity of wind power (around 9 gCO$_2$eq/kWh) which is in line with recent studies [80] ([12] assumed 25gCO$_2$eq/kWh). The GHG reduction potential in this study, at 80% to 90% GHG reduction potential, was, therefore, higher than in [12] (around 75% to 85%). The higher uncertainty in the GHG impact was observed in both studies for NH$_3$-fueled ICEs where N$_2$O emissions from ICEs are still not fully understood due to low technical maturity. With SCR it may be possible to control the N$_2$O emissions but, data on how SCR will influence N$_2$O emissions from ICEs is still not available.

LCA results also show that e-fuels produced using electricity from wind power seem to have an increased impact on human toxicity and resource use due to minerals and metals such as copper, zinc, and rare-earths, in addition to steel which was also highlighted in [12,13]. Wind power needs more material per energy output compared to other electricity production infrastructures [81]. This impact of materials used in wind farms may be reduced in the future if the materials are recycled or reused. Apart from minerals and metals used in the windmill, resource use is critical for electrolyzers, FCs, and batteries. Future studies should specifically analyze the material needed for these technologies and the availability of critical raw materials, as these are necessary for understanding material constraints for the fleet-level transition toward decarbonization pathways. This is valid not only for shipping but also for the decarbonization of other sectors.

The higher eutrophication potential of ammonia-fueled engines is related to the emission of nitrogen oxides and from the slip/leakage of

ammonia in engines and supply chain. It is critical to control the leakage/slip of ammonia and the emission of nitrogen oxides especially for the ships operating in emission control areas like the Baltic Sea. This is also discussed in other studies [12,82].

5.3. Economic impact from a life cycle perspective

Regarding LCC, among the assessed pathways, this study shows eMeOH or eNH$_3$ in ICEs have lower costs for all ship types assessed. eNH$_3$ performs slightly better than eMeOH even though lower efficiency for NH$_3$-based ICEs is considered. This is due to higher overall energy efficiency in NH$_3$ fuel production compared to MeOH. The BE option and FC options can potentially be cost-effective if the capital cost comes down or the e-fuel price is high. Higher utilization of capital equipment, like batteries and FCs, is another aspect that should be considered as higher efficiencies that offer lower fuel consumption can compensate for the higher capital cost. Korberg, et al. [18] also mentioned that higher fuel utilization favors BE and FCs. The utilization rate is the term used by Korberg, et al. [18] and is defined as hours spent in operation to represent the utilization of capital equipment. An alternative way of formulating a capacity utilization rate is by including factors such as the amount of energy, installed capacity, load of propulsor, and hours spent in operation. Therefore "annual energy use in vessel per installed capacity" can be used as a definition of "capacity utilization rate". The annual energy use determines the annual fuel consumed and depends on the time of operation and engine/fuel cell loads. Also, the installed capacity of the equipment onboard determines the investment cost. Utilization rates would be useful for evaluating fleets consisting of various vessels types and making decisions about the type of onboard technology to install.

When compared with SIICE as in the study [12], SIICE has lower efficiency resulting in the consumption of a higher amount of e-fuel compared with 2S/4SICE. In addition, a share of fossil-based pilot fuel in the total fuel consumption in 2S/4SICEs implies that a less proportion of e-fuel is required. The share of pilot fuel results in a lesser fuel-related cost for 2S/4SICE, compared to the FC or SIICE which is entirely fueled by renewable fuels. This is an important aspect to consider when developing policies as the amount used for fossil fuel as pilot fuel also needs to be controlled to achieve GHG emission reduction. Other studies, such as those by Stolz et al. [19] and Horvath et al. [20], have found eNH3SOFC and eLH2PEMFC (excluding fuel distribution costs) to be cost-effective options, respectively. Korberg et al. [18] also found eMeOH to be a more cost-effective choice compared to other e-fuels and eLH$_2$. Percic et al. [17] found that up to 30 nautical miles, battery-electric vessels can have a lower total cost than diesel-powered ships without considering charging infrastructure. The main differences between the studies are the cost of the fuel assumed and this study shows that fuel cost is the highest contributor to the LCC.

5.4. Carbon abatement cost

The CACs in this study are 240 €/tCO$_2$ to 400 €/tCO$_2$ for the RoPax vessel case, 250 €/tCO$_2$ to 600 €/tCO$_2$ for the tanker case, and 250 €/tCO$_2$ to 2000 €/tCO$_2$ for the service vessel case are similar to Kanchiralla et al. [12] with a range from 300 €/tCO$_2$eq to 550 €/tCO$_2$eq for a RoPax vessel and Lindstad [18] with a range from 150€/tCO$_2$ to 650 €/tCO$_2$ (ship type not specified). For RoPax, Battery electric has the lowest CAC and the highest for methanol in fuel cell. Ammonia in engines is found to be having lowest CAC for tanker and service vessel, whereas hydrogen in fuel cell has the highest CAC for tanker and methanol in fuel cells is the highest for service vessel. The CAC value is sensitive to the efficiency of the powertrain as higher efficiency results in the burning of less fuel which reduces the overall emission for the same functional unit and reduced fuel consumption results in lower fuel-related operational costs.

This study shows the importance of assessing different ship cases individually based on operation profile, before choosing a decarbonization pathway. This study also shows that policies like a carbon tax would affect the different decarbonization pathways differently. For example, in contrast to the ammonia engine, which emits primarily N$_2$O, the MeOH engine, which emits primarily CO$_2$, would be adversely affected by a carbon tax only applied to CO$_2$ emissions. In addition, the decision is sensitive to changes in the price of electricity, which in turn is highly dependent on demand from other sectors.

5.5. Safety

Regarding safety, the hazards associated with the new fuels and systems need to be properly contained and managed. Regulations for the use of ammonia and hydrogen onboard vessels are not yet mature but are under development by the International Maritime Organization and will be part of the International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF Code) [73]. Draft interim guidelines for ships using hydrogen as fuel were agreed on at the IMO's Sub-Committee on Carriage of Cargoes and Containers (CCC7) [74]. Work is underway to develop guidelines for the safety of ships using ammonia as fuel, with initial work on the collection of safety information reported in 2022 by Japan [75]. Ship classification society guidance documents on the use of hydrogen [76,77] and ammonia [78,79] were considered during the conceptual design for the case vessels.

The results of this study and its approach could be useful on a general level as they indicate that certain renewable fuel and propulsion options must be adequately weighted also in relation to the variations and potential changes in the scenario of linked parameters. The developed approach for conducting an environmental and cost analysis could be useful for improving similar but more static studies also in other areas.

6. Conclusion

The study gave a detailed and systematic comparison of the differences in the environmental and techno-economic performance over the life cycle between three specific ships (RoPax, tanker, and service vessel) and selected fuel and propulsion pathways (electricity and e-fuels) for the system boundaries chosen. Liquid hydrogen in fuel cells has the highest GHG reduction potential for the RoPax and the service vessel cases. Ammonia in the solid oxide fuel cell has the highest GHG reduction potential for the tanker. Ammonia and methanol in ICEs were found to be cost-competitive for reducing GHG emissions for all ships, however sensitive toward utilization rate and fuel cost. The higher capital cost and shorter lifetime for FCs and batteries have a significant effect on the cost competitiveness of these technologies. Results also indicate that high utilization rates and less energy between bunkering operations can make battery-electric more cost-competitive than the other energy carriers investigated in this study. It may be noted that the study is limited to only three types of ships, future studies can be directed to include more ship types for a better understanding of the energy transition of the shipping fleet. Future studies could also take into account the location of fuel production based on the availability of feedstock and the fuel distribution between production sites and bunkering.

CRediT authorship contribution statement

Fayas Malik Kanchiralla: Conceptualization, Formal analysis, Methodology, Validation, Visualization, Writing – original draft. **Selma Brynolf:** Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing, Methodology. **Tobias Olsson:** Conceptualization, Formal analysis, Writing – review & editing. **Joanne Ellis:** Formal analysis, Methodology, Supervision, Writing – review & editing. **Julia Hansson:** Funding acquisition, Supervision, Writing – review & editing, Validation. **Maria Grahn:** Funding acquisition, Supervision, Writing – review & editing.

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

The additional data and results as part of the article are available in the document titled 'Supplementary Information- How do variations in ship operation impact the techno-economic feasibility and environmental performance of fossil-free fuels?: a life cycle study'. The document includes three sections: Section S1 provides more details on methodology, Section S2 covers more details on the inventories used in the assessment, and Section S3 gives detailed results including the intermediate results from the assessment. Results also include the LCA and LCC results for functional unit annual operation. Supplementary data to this article can be found online at [https://doi.org/10.1016/j.apenergy.2023.121773].

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