Supplementary information

Life Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free Shipping

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This supplementary information provides all background information to the publication and covers details on the methods, case study, technical description, background materials, motivation on the assumption, inventory data, and detailed supplementary results used in this study. The SI also includes detailed results like results before normalization, uncertainty analysis, and scenario analysis used in this study. The document contains 34 pages, 28 Figures, and 14 Tables.
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S1: Applied methodology and detailed description

In line with the objective of the energy performance, environmental performance, and economic performance are investigated from the life cycle perspective including all life cycles from cradle to grave of a product or service. The prospective life cycle assessment (pLCA) and environmental life cycle costing (eLCC) are methodologies used in this study for environmental and economic assessment taking care of their entire life cycle from cradle to grave. The standardized guidelines of ISO 14044:2006 standard are used in four phases: 'goal and scope definition', 'inventory analysis', 'impact assessment', and 'interpretation' in an iterative process [1]. The technologies assessed in the option are in the early stages of development and need to be modeled at a future point in time, and should include the likely development in the goal, scope, and inventory modeling. Future-oriented LCA studies also called ex-ante LCA is used for the assessment of emerging technologies or consequences of the introduction of new technologies. The pLCA comes under the scope of ex-ante LCA is used [2] (terminology used in different literature is different). emerging technology is scaled-up to include technology development and using likely performance at full operational scale [2, 3]. The midpoint level is used in this study as a higher number of impact categories and the results are more accurate and precise compared to the three areas of protection commonly used at the endpoint level [4].

Life cycle costing (LCC) is a tool for assessing the economic dimension of sustainability and is capable to support decision-making at different stages of the life cycle [5]. Rödger et al. [5] distinguish LCC into conventional LCC, environmental LCC, and societal LCC. The eLCC method is aligned with the LCA study in terms of system boundaries, functional units, and methodological steps [5]. In LCC, analysis is done based on cost flows in terms of expenses (outflow) and revenue (inflow) over different life cycle phases. In eLCC, environmental emissions or wastes from the system would also be internalized in terms of monetary value. In this study, sensitivity analysis is done assuming an anticipated carbon tax on fossil-based CO$_2$ emissions. Another aspect of LCC is that there are several stakeholders involved in different life cycle phases and each stakeholder has a different type of impact. For aggregating the cost simply adding the costs of all actors in the life cycle will not work as the expense of one actor is the revenue of another [5]. The LCC can be performed for multiple actors, however, this study focuses on ship owners and operators. For example, the costs flow associated with manufacturing components (energy costs, material costs, transportation, etc.) are expenses to the manufacturer whereas the acquisition cost is revenue. Figure 1 shows the main steps of the pLCA and eLCC methodology.
S1.1 Functional unit and time horizon

In eLCC and pLCA, the functional unit is key to comparing the cases and should be a quantifiable reference flow representing the product system's function [1]. The functional unit used in the study is one round trip of a RoPax vessel from Gothenburg to Kiel and back to Gothenburg. The pLCA studies emerging technologies when the knowledge is sparse [3] and considers the environmental performance at a time in the future when the technology is likely to get developed. It is assumed that the technologies are developing at a faster pace in recent years and would be matured by end of this decade, the time horizon considered for this study is 2030, these solutions will be get developed within 10 years and would be matured by end of this decade. Further, it is assumed that the ship operates for 25 years before the ship is disposed of. The study is made in a European context, and targeted audience includes ship owners, operators, academia, policymakers, and LCA practitioners.

S1.2 Case study vessel details

The vessel considered in this study is traveling on a fixed route of roughly 230 nautical miles between Gothenburg (port 1) and Kiel (port 2). Round trip energy data is calculated using the data measured from the cruising phase, maneuvering phase, and Mooring phase of a single trip, and hotel load is assumed as 75% of maximum load. The main particulars of the case study ship are shown in Table S1. The propulsion system for each case study is designed based on the reference ship's voyage route and operation profile considering the maximum propeller load of 20MW, maximum hotel load of 2 MW, the maximum auxiliary load of 2 MW, and the additional energy loads required for the operation of components like reformer, onboard carbon capture, etc., and to compensate for the energy losses during the operation of components.

### Table S1: Main particulars of the case study vessel including the energy load during the entire round-trip operation.

| Vessel type | RoPax Ferry | Energy load of the ship during the round trip |
|-------------|-------------|---------------------------------------------|
| Route       | Gothenburg - Kiel | Cruising                                  |
| Length      | 240 m       | Propeller mechanical load (kWh) 382 500    |
| Deadweight  | 10130 MT    | Auxiliary electrical load (kWh) 31 600     |
| Design speed| 19 knots    | Thermal heat load (kWh) 31 200              |
| Passenger capacity | 1300 | Maneuvering                              |
|             |             | Propeller mechanical load (kWh) 22 400     |
|             |             | Auxiliary electrical load (kWh) 5 800      |
|                        |                        |                        |                        |                        |
|------------------------|------------------------|------------------------|------------------------|------------------------|
| **Vehicle capacity**   | 300                    | **Thermal heat load (kWh)** | 5 000                  |
| **Annual round trips** | 182                    | **Port 1 - electrical (kWh)** | 12 000                |
| **Service Life**       | 25 years               | **Port 2 - electrical (kWh)** | 9 800                 |
| **Mooring**            |                        |                        |                        |                        |

**S1.3 Technological options**

In this study, the following nine propulsion options that also need to meet Tier III requirements are analyzed from a life cycle perspective. These propulsion scenarios are modeled by selecting major components and their likely development by 2030. In addition to the load profile of the ship, the component size and capacity also depend on the additional loads, the efficiencies of the other associated components, and the availability of excess heat from the engine. During the mooring phase, the only electrical load is considered and is assumed from the respective port uniformly for all the cases. Reserve capacity for the storage tank is assumed as 30% of the total fuel required for the round trip.

**Case 1 MeOHICE** is a propulsion option fueled by eMeOH in a dual-fuel engine with SCR and the pilot fuel is MGO (Figure S2). The total engine power required for the operation is 21 MW. The shaft generator is required only to meet the auxiliary electrical load. The excess heat from the engine is used with help of waste heat recovery (WHR) to meet the heat requirement during cruising and maneuvering. eMeOH and MGO are stored in normal storage tanks.

**Case 2 MeOHICE w PostCC** is a dual fuel engine fueled by eMeOH with post-combustion OCCS and the pilot fuel is MGO (Figure S2). The total engine power required is 25 MW due to the higher energy required for the additional component. The shaft generator is required for meeting the auxiliary load and additional energy for the heat pump, OCCS, and CO₂ chiller. eMeOH and MGO are stored in service tanks and liquid CO₂ is stored in insulated cryogenic tanks. Excess heat from the engine is used in OCCS operation. The CO₂ captured onboard is circulated back for eMeOH production onshore.

**Case 3 HyMethShip** which is detailed in the study by Malmgren et al. [6]. In this case, eMeOH is used as an energy carrier and stored onboard (Figure S2). The eMeOH is cracked in a reformer into H₂ and CO₂. CO₂ is separated with the help of membranes in the reformer. The H₂ is burned in the 25 MW spark-ignition engine coupled with a generator. Electric propulsion is considered to meet the torque requirement. The engine is optimized for producing high-quality heat to use in the reformer and CO₂ adsorption chiller. For startup and power ramping a 5 MWh battery storage system is considered. The NOx emissions from engines are below the Tier III requirement [6]. The eMeOH is stored in service tanks and liquid CO₂ is stored in insulated cryogenic tanks. The CO₂ captured onboard is circulated back for eMeOH production.
Case 4 eLH2ICE is H₂-fueled in a spark-ignition engine, where eH₂ is stored as liquid (eLH₂) (Figure S3). The engines are coupled with the generators with a total power output of 24 MW and SCR is not considered. eLH₂ must be stored below -253°C and require special vacuum insulation tanks. The excess heat from the engine is used with help of WHR to meet the heat requirement.

Case 5 eNH3ICE is a propulsion option fueled by eNH₃ in spark-ignition engines which are coupled with the generators with a total power output of 24 MW (Figure S3). The electricity for the heat pump and auxiliary load also comes from these generators. The system uses H₂ as pilot fuel which is generated using an NH₃ reformer operated from excess heat from the engine. The system uses a 5 MWh battery storage system for startup and power ramping. SCR system is required for reducing NOx emissions, SCR in this system can utilize NH₃ from the engine slip as a reducing agent. NH₃ storage can be stored as a liquid when pressurized above 18 bar [7] and is stored in pressurized storage tanks.

Case 6 eLH2PEMFC is powered using PEMFC fueled by H₂, where eH₂ is stored as eLH₂ (Figure S3). The total power output of 24 MW. Since the energy output is electrical, it can be directly used for the electrical propulsion, heat pump, and auxiliary load. eLH₂ is stored in special vacuum insulated tanks below -253 °C. PEMFC is the most commercialized fuel-cell type and operates with high purity H₂ to avoid electrolyte/electrode poisoning [8].
**Case 7 eNH3SOFC** is powered using SOFC fueled by eNH$_3$ with a total power output of 23 MW (Figure S4). The electrical output is directly used for electrical propulsion, heat pump, and auxiliary load. eNH$_3$ is stored as a liquid in tanks pressurized above 18 bar. For startup and power ramping the system uses a 5MWh battery storage system. SOFCs are selected for NH3 as i) Zirconia-based solid electrolyte is stable in NH3, ii) High temperature allows internally reforming of NH3 into H2 and nitrogen with help of a catalyst, and iii) The excess heat generated from the chemical reaction can be utilized for NH3 reforming [9].

**Case 8 BE**, where the electricity is stored in batteries and used for the ship operation and is charged using electricity from the port (Figure S4). The battery is sized for a round trip with a capacity of around 700 MWh including a 30% reserve capacity. Power is managed using the control unit and is directly used for electrical propulsion, heat pump, and auxiliary loads.

**Case 9 MGOICE** is the reference case where fossil MGO is fueled in a conventional medium-speed diesel engine is the reference case (Figure S4). The total engine power required for the operation is 21 MW with SCR. The shaft generator is required for meeting the auxiliary electrical load. The excess heat from the engine is used with help of WHR to meet the heat requirement.
S1.4 LCC methodology

The cost flows around the processes are different from pLCA and so is the system boundary for foreground system and background system as shown in Figure S5, the round-trip cost constitutes cost from different life cycle phases and the cost is incurred in different time frames and period. The cost flows are considered in Euros (€) with the base year 2021 and are estimated for the year 2030. The number of annual trips (t_a) is 182 and the service life of ship (n) and infrastructure is considered for 25 years. Capital recovery factor (crf) is considered for fuel infrastructure and capital equipment, with a discounting rate of 3%.

**Manufacturing phase:** The cost of each component is decided based on the sizing and rating, which are detailed in Table 2 and Table 3 for each propulsion system option. The total equipment cost (TEC) of a given propulsion system is calculated by adding the cost of all the components required for the given system. Equation 2 is used to convert the purchase cost towards the round-trip termed as acquisition cost ($C_A$).

$$C_A(€/round\ trip) = \frac{TEC \times crf}{t_a}$$  \hspace{1cm} (2)

**Fuel production phase:** The energy carriers selected for this study are fossil-based MGO, fossil-based LNG, eMeOH, eLH₂, eNH₃, and electricity mix costs are calculated as part of the study considering all the input prices. MGO and LNG are traded presently in the market and major changes are not expected by 2030 in terms of the production processes except due to supply and demand. For these fuels, the cutoff price is taken from the 2021 yearly average. For the other alternative fuels, the fuel cost ($F_C$) (in €/MWh_fuel) is calculated by considering all the upstream costs (details in supporting information section S2.2). The fuel cost for the round trip ($C_F$) is dependent on the amount of fuel consumed in the round trip ($F_R$) as in equation 3.

$$C_F(€/round\ trip) = F_C(€/kg) \times F_R(kg)$$ \hspace{1cm} (3)

**The replacement cost:** Some capital equipment needs to be replaced due to the lesser operational life of the component compared to the service life of the ship (e.g. batteries). Replacement cost is
different for each component and is based on the number of replacements (Nr); all replacements required for propulsion to be summed to get the total cost. The replacement cost for the round trip (CR) is calculated using equation 4, where Nc is the number of components that require replacement, and Rc is the cost for each replacement.

\[ C_R = \sum_{i=1}^{Nc} Nr \times Rc \times crf \times t_s \]  

(4)

**Operation phase:** During the operation life of the ship there are different costs associated with the consumables (Cc) (e.g.: urea used in SCR, MEA used in OCC, etc.), operation/overhead cost (Co), and service/maintenance cost (CM). The prices for the consumables are determined by market prices and are directly taken into the calculation. The operation cost excluding the replacement cost and fuel cost for the round trip is termed C_OMC in the study and calculated using equation 5.

\[ C_{OMC} = \frac{C_0 + C_M + C_C}{t_a} \]  

(5)

**EOL phase:** The EOL phase is considered in the background system, only the scrap values for the components are analyzed. This depends on the material composition of the components. In this analysis the scrap value for the metals (the reference year 2021) for calculating the total value that can be recovered. The material will get recovered only at the end of the life of the component, considering that there would be inflation in the material price. The discount rate is not used in this case. End-of-life cost for the round trip (CEOL) is treated as revenue in this study and calculated using equation 6.

\[ C_{EOL} = \text{Amount of metal in component (kg)} \times \text{scrap value of metal (€/kg)} \times t_a \times n \]  

(6)

**External cost:** The CO2 emitted during fuel consumption is expected to be internalized by 2030. In this study, only the CO2 emission is used to calculate the environmental costs. The internalized environmental cost (CE) for operation phase emissions is calculated in this phase in addition to the cost for CO2 transportation for permanent storage (equation 7). This study uses 150 €/tonne of CO2 as the anticipated carbon tax during 2030 [10].

\[ C_e(€/round trip) = \text{Tax rate (€/kg)} \times \text{emissions during round trip (kg)} \]  

(7)

**Revenue loss:** Due to differences in the volumetric efficiency of the fuel, power densities of different energy conversion technologies, and additional components like CC, reformer, etc. additional volume is required on-board of ships. For ferries, volume loss is considered more important than tonnage loss and space loss cost (CSL) is assumed at 8 €/m³ as in the study by Korberg et al.[11]. The revenue loss (CRL) is calculated using equation 8, where VA is the additional volume required.

\[ C_{RL}(€/round trip) = C_{SL}(€/m^3) \times V_A (m^3) \]  

(8)

Finally, the total life cycle cost for the round trip (functional unit) including all the life cycle phase costs for the round trip of case RoPax vessel is shown in equation 9:

\[ \text{Total life cycle cost (€/round trip) = } C_A + C_F + C_{OMC} + C_R + C_E + C_{EOL} + C_{RL} \]  

(9)

### S1.5 Limitations

Due to the different volumetric and gravimetric energy densities of the fuel/battery, the volume and weight of the fuel tanks onboard would be different. Also, the power density of ICEs and FCs varies with different options. The potential impact on the ship operation due to the difference in
weight/volume of these systems is not addressed in this study. Another limitation of the study is
regarding the system boundary, that the scope does not include the port infrastructure required for
each fuel type nor the transportation of fuels from the production facility to the port. Considering
that the ship structure and components other than the propulsion/fuel system would be the same
for all the cases, it is not considered in the study. Although a higher amount of charging and
discharging cycle has a negative effect on the battery life, charging cycles for the batteries are not
considered in the study.

S2: Inventory details

S2.1 Fuel properties
The properties of the fuels studied are given in Table S2.

|                        | Liquid Ammonia [12] | Liquid Hydrogen [12] | Methanol[13] | MGO         |
|------------------------|---------------------|----------------------|--------------|-------------|
| Boiling point [°C]     | -33.4               | -253                 | 65           | 200-385     |
| Lower heat value [MJ/kg]| 18.8               | 120                  | 19.9         | 42.7        |
| Auto ignition temperature [°C] | 651              | 571                  | 439          | 250         |
| Flammability Limits in air [vol.%] | 15-28        | 4.7-75               | 7.3-36       | 0.5 -5      |
| Density (kg/m³)        | 682.6               | 70.8                 | 791.4        | 855         |

S2.2 Fuel production phase
MGO is the only fossil-based fuel considered in the study which is considered a background
process and inventory details are taken from the Ecoinvent 3.7.1 (diesel production, low-sulfur,
petroleum refinery operation | diesel, low-sulfur | Cutoff).

Electricity is used for four applications, i) fuel production/liquefaction, ii) component production,
iii) mooring at Gothenburg port (both for energy use/charging batteries), and iv) mooring at Kiel
port (both for energy use/charging batteries). For each application, the source of electricity varies
and has different associated costs and emission factors. For fuel production of eLH₂, eNH₃, and
eMeOH, the renewable electricity considered in the study is from onshore wind power with LCI
data from Ecoinvent 3.7.1. For the component production application, electricity is assumed from
the European electricity mix as the component is assumed to be produced in different locations in
Europe. During mooring at Gothenburg port, the Swedish electricity mix is considered. At Kiel
port, during mooring German electricity mix is considered. Electricity mixes are based on
projected scenarios for the time horizon 2030 by the EU Commission based on the reference year
2020 and present member policy [14] as shown in Table S3.

| EU mix [14] | Swedish mix [14] | German mix [14] | Description of the LCI database                                      | Reference     |
|-------------|------------------|-----------------|---------------------------------------------------------------------|---------------|
| Nuclear energy | 17.3%            | 28.3%           | 0.0% electricity production, nuclear, pressure water reactor       | Ecoinvent 3.7.1 |
| Solid       | 9.0%             | 0.0%            | 20.4% electricity production, hard coal | electricity, high voltage | Cutoff       | Ecoinvent 3.7.1 |
| Oil         | 0.2%             | 0.0%            | 0.2% electricity production, oil | electricity, high voltage | Cutoff       | Ecoinvent 3.7.1 |
| Gas         | 14.5%            | 0.8%            | 15.7% electricity production, nuclear, pressure water reactor     | Ecoinvent 3.7.1 |
|             |                  |                 | electricity, high voltage                                         |               |

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**Hydrogen** can be produced from different feedstock and presently over 95% of the current hydrogen is produced from fossil fuel-based energy sources [15]. The study focuses on eH₂ which is produced by electrolysis of water using renewable energy. The study from Delpierre et al. [16] suggests that there is no significant variation in environmental impact between the PEM electrolyzer and the alkaline electrolyzer. As the alkaline electrolyzer is more mature and less expensive, this study only considers alkaline electrolyzer. This study uses inventory data for an alkaline electrolyzer from the LCA study by Delpierre et al. [16]. The production of 1 kg of hydrogen requires 50 kWh of electricity, 10 kg of water, and 1-2 g of potassium hydroxide [16]. Another possibility is to use a solid oxide electrolyzer, however, the cost of solid oxide electrolyzers is high that it is not cost-competitive with other electrolyzers [17] and hence not considered in the study. The LCI data for the electrolyzer is assumed from the study by Delpierre et al. [16].

**Liquid Hydrogen** is produced by liquefying the hydrogen whose boiling point is -253°C, theoretically, a minimum of 3.3 kWh of energy is required for liquifying 1 kg of hydrogen [15]. The results from the IDEALHY project show that the liquefaction of H₂ can be achieved with 6.4 kWh/kg using a reverse Brayton cycle [18] which is assumed for this study considering that it would achieve commercial operation by 2030. For sensitivity analysis, energy for liquefaction is considered from 6 kWh/kg to 7 kWh/kg [15] (main article Table 5). The LCI and cost for the hydrogen liquefaction plant infrastructure are assumed from the IDEALHY project [18].

**Methanol** is also presently produced mainly from fossil fuels and can be produced from different feedstock including biomass and renewable energy sources [6]. eMeOH is produced using renewable energy, eH₂, and captured CO₂. For cases 2 and 3 the major share of CO₂ comes from capturing CO₂ from the onboard ship depending on the capture rate. The remaining CO₂ is considered from DAC based on the solid sorbent process. Leakage during the storage and transportation of CO₂ is assumed to be 1%. For case 5, it is considered that the entire CO₂ required comes from DAC. In this study, it is considered that producing 1 kg of eMeOH requires 1.375 kg of carbon dioxide, 0.189 kg H₂, and 0.858 kWh of electricity and heat [19]. During MeOH synthesis some byproducts get emitted to the air: CO₂ (7.65E-6 kg/kg MeOH), CO (6.9E-7 kg/kg MeOH), and MeOH (0.00172 kg/kg MeOH) [19]. The DAC technology used in commercial-scale DAC plants operated by Climeworks in Hinwil and Hellisheïði is by cyclic temperature-vacuum swing adsorption and LCA has been conducted by Deutz and Bardow [20] for this plant. The same is considered in this study. The DAC plant encompasses the foundation, CO₂ collectors, process unit, auxiliaries, and the adsorbent [20]. Considering the time horizon of this study, the operation of the plant requires 3 g adsorbent per kg CO₂ captured, 0.5 kWhₜₜ and 1.5 kWhₜₜ [20]. The thermal energy required for the process is assumed to be produced using electricity, hence the electricity
input is taken instead of the heat input. The LCI and cost for the eMeOH synthesis infrastructure are taken from Ecoinvent 3.7.1 and DAC infrastructure is considered from the study by Deutz and Bardow [20].

Presently ammonia is produced using Haber Bosch plants using fossil feedstocks – natural gas (50%), oil (31%), and coal (19%) [21]. This study focuses on eNH$_3$ and there are multiple pathways for producing it such as the Haber Bosch process (TRL 9), electrochemical process (TRL 1-3), photocatalytic (TRL 1-3), biological (TRL 1-3), and non-thermal plasma (TRL 1-3) [21]. In this study, it is considered that eNH$_3$ is produced using the Haber Bosch process using eH$_2$ and nitrogen. The production of 1 kg eNH$_3$ requires 0.177 kg eH$_2$, 0.823 kg nitrogen, and 0.472 kWh of electricity [21]. From this process, the output is liquid NH$_3$. Nitrogen can be obtained with an air separation unit, cryogenic air distillation is a low-cost technology that can deliver high purity nitrogen in high volumes [22]. For separating 1 kg of nitrogen through cryogenic air distillation, 0.314 kWh of electricity is required [22]. NH$_3$ can be stored as a liquid above 18 bar pressure [7].

The study includes the fuel production infrastructure required to produce the above fuels. These fuel production facilities are considered to be located near the Gothenburg port, this reduces transportation and additional storage requirements, and the fuel distribution and bunkering infrastructure are not considered in the study. The LCI detail and cost of the infrastructures considered in this study are given in Table S4.

Table S4: LCI background data used for the fuel production infrastructure.

| Infrastructure          | Description                                      | Ref             | Service life | CAPEX           | O&M cost | Ref  |
|-------------------------|--------------------------------------------------|-----------------|--------------|-----------------|----------|------|
| Hydrogen liquefaction plant | Hydrogen liquefaction plant based on reverse Brayton cycle | [23]            | 25           | 2100 €/kgLH$_2$/day | 4%       | [23] |
| Direct air capture plant   | Direct air capture plant based on temp-vacuum swing adsorption | [20]            | 30           | 271 €/kgCO$_2$/day | 5%       | [24] |
| Electrolysis plant | Alkaline electrolysis plant | [16]            | 30           | 570 €/kW        | 5%       | [17] |
| Electro-methanol plant | Methanol factory construction | Ecoinvent 3.7.1 | 30           | 69 €/tMeOH/day   | 5%       | [17] |
| Air separation unit | Air separation facility construction | Ecoinvent 3.7.1 | 30           | 376 €/kgN$_2$/day | 5%       | [22] |
| Ammonia plant | chemical factory construction, organics | Ecoinvent 3.7.1 | 30           | 174 €/tNH$_3$/day | 5%       | [17] |

S2.3 Component manufacturing and end of life

Engine and SCR: During the engine manufacturing phase, the major emission is associated with the raw material and energy. The typical raw material composition used in the study is used from the study by Joeng et al [25] is shown in Table S5. The construction and weight depend on the type of engine which varies with the fuel used, the weight details for the MGO engine and MeOH DF engine are adopted from the manufacturers' catalog based on the power rating [26]. Selective catalytic reduction (SCR) is used for engines operated with MGO, eMeOH, and eNH$_3$. However, SCR requires high exhaust gas temperature and the addition of Urea or NH$_3$ for efficient reduction. If SCR is available, the engine can operate on a high fuel-efficient setting often associated with higher NOx from the engine (before SCR) [27]. This ensures that there is no major loss of efficiency. The activating element on the catalyst is assumed as TiO2 and is around 0.25% of the weight of SCR[28]. Based on the manufacturers’ opinion, while operating with low sulfur fuels, the catalysts of SCR shall be replaced once in a lifetime of the ship.
Table S5: The material and energy details of the marine engine considered in the study.

| Material required                      | Quantity | Reference |
|----------------------------------------|----------|-----------|
| Chromium steel (weight ratio %)        | 40       | [25]      |
| Cast iron (weight ratio %)             | 46       | [25]      |
| Aluminum (weight ratio %)              | 8        | [25]      |
| Copper and Zinc (weight ratio %)       | 0.2      | [25]      |
| Lead (weight ratio %)                  | 0.1      | [25]      |
| Plastic (weight ratio %)               | 0.9      | [25]      |
| Rubber (weight ratio %)                | 0.9      | [25]      |
| Electricity (kWh/kW)                   | 10.8     | [29]      |

**PEMFC:** Fuel cells convert the chemical energy of H₂ to electricity through electrochemical oxidation. As the conversion is direct and no need for high combustion temperatures, fuel cells offer higher energy conversion efficiency than conventional energy systems[9]. Low-temperature polymer electrolyte membrane fuel cell (PEMFC) systems are currently the most preferred technology for most transport applications since they have a high power density and allow fast cold start-up and load transient, especially if pure H₂ is available [30]. The materials for PEMFC cell and balance of plant (BoP) are adopted from the study by Stropnik et al. [31] is shown in Table S6.

Table S6: The material and energy details of the PEMFC considered in the study.

| Component          | Material type               | Quantity |
|--------------------|-----------------------------|----------|
| PEMFC cell         | Graphite (kg/MW)            | 4 500    |
|                    | Polyvinylidene chloride (kg/MW) | 1 100. |
|                    | Aluminum (kg/MW)            | 300      |
|                    | Chromium steel (kg/MW)      | 100      |
|                    | Glass fibers (kg/MW)        | 100      |
|                    | Perfluorosulphonic acid (kg/MW) | 70   |
|                    | Carbon black (kg/MW)        | 0.8      |
|                    | Platinum (kg/MW)            | 0.75     |
| Balance of Plant   | Steel product (kg/MW)       | 3 700    |
|                    | Polyethylene high density granulate (kg/MW) | 1 500 |
|                    | Chromium steel (kg/MW)      | 1 100    |
|                    | Cast iron component (kg/MW) | 800      |
|                    | Aluminum (kg/MW)            | 750      |
|                    | Polypropylenes granulate (kg/MW) | 250  |
| System             | Electricity consumption (kWh/MW) | 16 900 |

**SOFC:** While using NH₃ as the source of H₂ in a fuel cell, PEMFC is not preferred as even traces of NH₃ can poison the fuel cell [30]. The study by Kishimoto et al. [9] demonstrated the performance and durability of NH₃-fueled SOFC stacks. The materials for SOFC cells are still under continuous development, especially for NH₃, the material composition is modeled based on the available literature. For this study, the material composition and weight for the SOFC are based on the study by Al-Khori et al [32] and input obtained from the SOFC manufacturer during the interview. The material for manufacturing is modeled according to the raw material used in the chemical composition and is shown in Table S7, and due to lack of data on the auxiliary materials like solvent, binders, and energy required for producing the stack is not included in analysis.

Table S7: The material and energy details of the SOFC considered in the study.

| Component          | Material type [9, 32] | Quantity [32] |
|--------------------|-----------------------|---------------|

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OCC: Carbon capture is a complex and emerging process currently being implemented now on various industries e.g.: Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project in Canada, Gorgon Carbon Dioxide Injection Project in Australia, FutureGen 2.0 Project in the US, etc [33]. Due to limitations such as power demand, volume constraint, and stability, this method is difficult to be installed on ships [33]. There is a wide range of CO2 capture technologies available, including adsorption, cryogenics, absorption, microbial, and membrane [34]. Carbon capture using the chemical solvent Monoethanolamine (MEA) is a proven absorption technology used in various projects [35].

Since the OCC application requires additional power, additional engine power is provided for the operation of CCS making sure that the energy requirement for ship operation is not affected. The CCS capacity is modeled based on previous studies by Luo and Wang [35] and Giordano et al. [36]. The capacity of the CCS system depends on the CO2 content of exhaust gas is different based on the fuel and the CO2 capture rate. The OCC system is sized in this study by proportionating the power demand of the CCS system used in the study by Giordano et al. [36]. Based on this the OCC requires 1.4 MWel for capturing CO2 from the MeOH engine exhaust. It is assumed that the excess heat from the engine can meet the thermal energy requirement for the OCC for all the systems. Kleijn et al. [37] estimated the steel demand for CC installation for 400 MWel is around 3700 tonnes of carbon steel and 950 tonnes of stainless steel. For this study, the materials required are scaled proportionally based on the max CO2 emission rate from the engine which is 12.73 tCO2/h, in addition, the compressor capacity of 821 kW is required to liquefy CO2. The LCI data for compressor is taken from ecoinvent 3.7.1. Due to space limitation of the OCC equipments onboard, the base capture rate considered is 70%, however, for the Monte-Carlo simulation, the capture rate of a minimum of 60% and a maximum of 90% is analyzed.

Reformers: MeOH and NH3 reformers are used for producing H2 by cracking the MeOH and NH3 respectively. The MeOH reformer is used in case 4 and the technology is developed within the HyMethShip project, and it uses the excess heat from the engine for an endothermic reaction between MeOH and water to produce H2 and CO2. This reformer has an inbuilt membrane to separate H2 and CO2 and thus act as pre-combustion carbon capture. H2 is directed towards the engine as fuel and CO2 is liquefied and stored onboard with help of the adsorption chiller. The reactor is having 3 main parts, i) catalyst which supports the cracking process, ii) membrane with sealings for separating H2 and CO2, iii) reactor which forms the structure of the reformer. Based on expert feedback, it is assumed that the higher selectivity of the membrane will allow capturing 95% of CO2 produced and a maximum of 98%. The present result shows that more than 90% capture rate. This range is used in uncertainty analysis (main article Table 5). For case 6, the NH3 reformer is required only to generate pilot fuel (10% H2 by volume), and as the by-product is only nitrogen and can be directly used in the engine. However, the temperature for decomposing the

### Table 1: Material and Energy Consumption

| Material/Component | Mass Flowrate (kg/MW) | Energy Consumption (MJ/MW) |
|--------------------|----------------------|---------------------------|
| SOFC cell          | Cobalt oxide         | 46                        |
|                    | Strontium            | 7                         |
|                    | Lanthanum            | 45                        |
|                    | Nickel oxide         | 1136                      |
|                    | Yttrium oxide        | 53                        |
|                    | Zirconia             | 358                       |
|                    | Electricity consumption | 27280                  |
| Balance of Plant   | Chromium steel       | 39000                     |
|                    | Electricity consumption | 107500               |

[443x52] SI Page 16 of 34
H₂ is between 300 and 520°C depending on the catalyst [30]. Also, the catalyst should be stable in an NH₃ environment at these high temperatures. The detail of the reformer considered for this study is shown in Table S8.

| Table S8: The material and energy details of the reformers considered in the study. |
|-----------------------------------------------|----------------|----------------|
| Manufacturing data                          | Methanol reformer (kg) | Ammonia reformer (kg) |
| Alumina oxide (kg)                          | 7500            | 225            |
| Copper oxide (kg)                           | 18000           | 900            |
| Zinc oxide (kg)                             | 7500            | 375            |
| Stainless steel (kg)                        | 267000          | 13350          |

Absorption chiller system: The absorption chiller system is used to cool down and condense the gaseous CO₂ to liquid CO₂. The absorption chiller system is driven by the excess heat from the main engines. From the manufacturer, the weight of the chiller is calculated for the HyMethShip concept and the major material used in the absorption chiller is stainless steel.

Batteries: Presently, lithium-ion batteries are the most predominant power source for electric vehicles, among which lithium-rich NMC batteries have a higher economical energy density [38]. For this study lithium-ion battery with NMC 811 cathode and a graphite anode is considered. The material data is adopted from the LCA study on a Giga factory for battery manufacturing Chordia et al [39]. Considering the developments of the battery uncertainty analysis is performed for the storage capacity and battery cost which is shown in the main article Table 5.

Motor: The motor is used for electric propulsion and considers a synchronous motor, the weight details are adopted from the manufacturing catalog [40]. The material data and background inventory data are taken from the ecoinvent 3.7.1.

Alternator: The alternator is used for generating electricity onboard from the engines, the power capacity of the alternator depends on the electrical load. The weight details are calculated from the manufacturing catalog [41], and the material composition of the electrical generator is taken from the GREET database [42].

Heat pump: A heat pump is considered for supplying space heat requirements. The material specification and weight are calculated from the manufacturing catalog and material composition is taken from the study by Greening et al. [43] as shown in Table S9.

| Table S9: Materials required for the heat pump considered in the study. |
|-------------------|-------------------|
| Material          | Weight (%)        |
| Alloy steel (kg)  | 15,5%             |
| Reinforcing steel (kg) | 58,1%          |
| Copper (kg)       | 17,7%             |
| Elastomere (kg)   | 7,7%              |
| polyvinylchloride (kg) | 0,8%           |
| HDPE (kg)         | 0,2%              |

S2.4 Operation phase

In this phase, emissions from the engine primarily depend on the type of fuel and fuel consumption. Fuel consumption varies with the engine load and for this study, it is assumed that, an average engine load of 80% during cruising and 20% during maneuvering. The fourth IMO GHG study 2020 gives an empirical equation for the specific fuel consumption (SFC) as a function of engine load as shown in equation 1 [44] which is used in this study. The emission inventory for
the cruising and maneuvering is calculated separately. It may be noted that this equation is not applicable for fuel cells or batteries as it operates in modules and load can be varied by not operating some modules [30]. The efficiency of fuel cells decreases at a high load (higher than 80%) as stack voltage decreases due to higher fuel utilization [9]. However, this reduction is not considered in the study as it is assumed that the highest average load is assumed during cruising is 80%. One exemption in the inventory is the emissions considered during the operation phase. Considering that most of the emissions from the propulsion system are released as exhaust gases [6], inventory data during operation does not include emissions to water, soil, and noise.

\[
SFC_{ME,\text{load}} = SFC_{\text{base}} \times (0.455 \times \text{load}^2 - 0.710 \times \text{load} + 1.280) \tag{1}
\]

Since, the engines considered in this study are in different stages of development, from a diesel engine that has been on the market for decades to an H\textsubscript{2} and NH\textsubscript{3} engine that is yet to be tested for marine application. The emissions inventory data and fuel consumption for engines based on fuels MGO and eMeOH (cases 1 to 6) are based on different studies [44-47]. For H\textsubscript{2}-fueled engines (cases 7 and 8), the emissions are directly-measured from the engine developed for the HyMethShip project. Fuel consumption for these cases is assumed considering expert opinion. For NH\textsubscript{3} engine, the emission of nitrogen compounds is assumed to be the same as MGO and MeOH engines considering that SCR would reduce these emissions with help of a reducing agent. However, less Urea is required for MeOH as the NOx emissions would be less based on the data from the study by Brynolf et al. [47], and based on experts the NH\textsubscript{3} engine doesn’t need an external reducing agent as unburned NH\textsubscript{3} act can as the reducing agent. For SCR cases, the NOx and NH\textsubscript{3} emissions are adopted from the study by Andersson et al. [45]. The efficiency of engines is considered based on the experts from the ship design and higher efficiency is considered for CI and DF engines compared to SI engines, also an uncertainty range is considered in the base efficiency of the engine which is shown in the main article Table 5.

For marine applications, NH\textsubscript{3} engines are under development. Engine manufacturer Wärtsilä is presently testing a four-stroke engine running on an NH\textsubscript{3} blend and anticipates the development of the engine on pure NH\textsubscript{3} by the year 2023 [48]. MAN Energy Solutions is also developing an NH\textsubscript{3} two-stroke engine and is anticipated to be ready by 2024 [49]. There are no emission inventory data for this type of engine. In a recent study by Lhuillier et al. [12], the NH\textsubscript{3}H\textsubscript{2} mixtures are investigated in an SI engine in a series of experiments and mentioned that higher efficiency was obtained while burning NH\textsubscript{3} with 10% H\textsubscript{2} (by volume) under lean conditions. The results are similar to an early study by Frigo et al. [50]. Considering the poor combustion properties of NH\textsubscript{3}, it is assumed that 10% of H\textsubscript{2} by volume is used as a promoter and it is produced from NH\textsubscript{3} with help of a reformer. Based on 'experts' opinion, the emission-related to carbon would be the same as an H\textsubscript{2} engine assuming that this is not related to the burning of fuels as there are no carbon atoms in the fuel. These studies suggest that the exhaust contains high unburned NH\textsubscript{3} and NOx emissions because of fuel-bound nitrogen [12, 50]. The SCR can be used for converting the NOx using NH\textsubscript{3} in the exhaust. The experts suggest that proper tuning of the engine for optimal combustion of NH\textsubscript{3} can ensure that the NH\textsubscript{3} slip is enough to reduce NOx in SCR and can meet tier III requirements. Based on this it is assumed that the NH\textsubscript{3} and NOx emissions after SCR would be similar to emissions from current SCR systems. However, the emission of nitrous oxide is uncertain and for this study an uncertainty analysis is done with emission from 0.013 to 0.13 g/kWh (10 times) to understand the impact on GWP.
For PEMFC, during the electrochemical reaction, only water is produced as a byproduct and for SOFC, nitrogen and water are byproducts of combustion and based on experts, there won't be any notable emission of pollutants from fuel cells. The SOFC operates at high temperatures and the heat from exhaust can be used for space heating. The efficiency of different components also affects fuel consumption. Following are the assumptions considered in the study efficiency of 98% for electric motor [51], efficiency of 97% for alternator [41], 98% efficiency for the gearbox [51], 98% efficiency for the control unit [26], and COP of 4 for the heat pump [52].

Inventory related to the replacement, for optimal case the catalyst in the reformer, should be replaced every 3 years averaging to 7 times during 25 years of lifetime. The Batteries and fuel cells are considered to be replaced twice during 25 years of lifetime. It may be noted that the battery would either discharge during maneuvering and cruising or charge during mooring making it in active operation the entire period. Whereas fuel cells would be idle during the mooring. SCR catalyst is considered to be replaced once during the ship's lifetime.

For the HyMethShip system de-ionized water is required in the reformer (0.33 kg H₂O for 1 kg H₂). For PostCC operation, due to the degradation of the solvent, there are some materials that to be supplemented and some related emissions to air [36] as shown in Table S10.

| Consumables required                  | Quantity |
|--------------------------------------|----------|
| MEA, (kg/tCO₂-in)                    | 1.44     |
| Caustic soda, (kg/tCO₂-in)           | 0.12     |
| Activated carbon, (kg/tCO₂-in)       | 0.07     |
| Water, (kg/tCO₂-in)                  | 18.1     |

| Air emissions                        | Quantity |
|--------------------------------------|----------|
| Ar, (kg/tCO₂-in)                     | 54.8     |
| N₂, (kg/tCO₂-in)                     | 3202.2   |
| O₂, (kg/tCO₂-in)                     | 128.3    |
| MEA, (kg/tCO₂-in)                    | 0.06     |
| NH₃, (kg/tCO₂-in)                    | 0.03     |
| Formaldehyde, (kg/tCO₂-in)           | 2.4 x 10⁻⁴|
| Acetaldehyde, (kg/tCO₂-in)           | 1.5 x 10⁻⁴|

**S2.5 Cost details**

Total life cycle cost includes acquisition cost (Cₐ), fuel cost (C_F), operation and maintenance cost (C_OMC), replacement cost (C_R), external cost (C_E), EOL cost (C_EOL), and revenue loss (C_RL). Cₐ, C_R, and maintenance and operation part of C_OMC are based on Table 3 in the article. The consumable part of C_OMC cost includes urea consumption based on Table 4 and other consumptions like MEA, de-ionized water, caustic soda, etc. based on data given in S2.4. The unit price of the consumable is taken from the current market price. C_EOL is the end of life cost is calculated based on the recycling value of the material as shown in Table S11. C_RL is calculated using additional volume occupied by the different propulsion systems including the storage tanks, whose value is shown in Table S12. Whereas C_E is included in sensitivity analysis considering carbon tax for fossil-based emissions,
Table S11: The scrap cost of the material during the end of life.

| Material                          | Value (€/tonne) | Reference |
|----------------------------------|-----------------|-----------|
| aluminium                        | 1680            | [53]      |
| cast iron                        | 126             | [53]      |
| chromium                         | 600             | [54]      |
| lead                             | 1512            | [54]      |
| nickel                           | 5278            | [55]      |
| steel, chromium steel 18/8       | 898,8           | [54]      |
| titanium dioxide                 | 2000            | [54]      |
| copper                           | 4368            | [54]      |
| zinc                             | 672             | [54]      |
| Battery                          | 2407            | [55]      |
| platinum                         | 14815           | [55]      |

Table S12: The volume and weight of the propulsion system for the cases considered in the study.

| Case 1          | Case 2          | Case 3            | Case 4            | Case 5            | Case 6            | Case 7            | Case 8         | Case 9         |
|-----------------|-----------------|-------------------|-------------------|-------------------|-------------------|-------------------|----------------|----------------|
| Volume (m³)     | 764             | 1501              | 1383              | 1333              | 1129              | 798               | 1064           | 1743           |
| Weight (tonnes) | 603             | 1178              | 1121              | 775               | 875               | 661               | 1010           | 3554           |

Fuel distribution and storage cost is not included in the main analysis, however, the impact of this cost on total LCC is analyzed using the data listed in Table S13.

Table S13: Fuel distribution cost used for the study

| Fuel                                | Cost (€/GJ) |
|-------------------------------------|-------------|
| Electricity [56]                    | 10.2c       |
| Liquified hydrogen (LH2) [57]       | 11.6        |
| Methanol [57]                       | 0.6         |
| Ammonia [57]                        | 1.2         |
| Fossil conventional alternative [57]| 0.2         |
**S2.6 Datasets**

Different raw materials are used for manufacturing the components, and the LCI detail for these materials are taken from the existing database as a background process (Table S14).

Table S14: Materials considered in the manufacturing of different components and relation to the database.

| Materials     | Used in                                | Database                          | Description in database                                      |
|---------------|----------------------------------------|-----------------------------------|-------------------------------------------------------------|
| **Plastics**  |                                        |                                   |                                                             |
| Polyethylene  | Heat pump, LTPEMFC                      | Ecoinvent 3.7.1                   | market for polyethylene, high density, granulate.           |
| Polyvinyl     | Heat pump, LTPEMFC                      | Ecoinvent 3.7.1                   | market for polyvinylchloride, suspension polymerised.       |
| Sodium chloride|                                        |                                   |                                                             |
| Nylon         | Marine engine                          | Ecoinvent 3.7.1                   | market for nylon 6 | nylon 6 | Cutoff, S - RER |
| Silicon       | Marine engine                          | Ecoinvent 3.7.1                   | market for silicone product | silicone product | Cutoff, S - RER |
| Sodium fluoride| LTPEMFC                                | Ecoinvent 3.7.1                   | Sodium                                                        |
| **Polypropylene** | LTPEMFC                      | Ecoinvent 3.7.1                   | market for polypropylene, granulate | Cutoff, S - GLO |
| Glass fibre   | LTPEMFC                                | Ecoinvent 3.7.1                   | market for glass fibre | glass fibre | Cutoff, S - GLO |
| **Metals**    |                                        |                                   |                                                             |
| Chromium steel| Heat pump, SCR, OCC, alternator, marine engine, CO2 tank, gearbox, LTPEMFC, SOFC | Ecoinvent 3.7.1 | market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S - GLO |
| Nickel        | Heat pump, SOFC, Alkaline electrolyzers | Ecoinvent 3.7.1                   | market for nickel, class 1 | nickel, class 1 | Cutoff, S - GLO |
| Steel         | Alkaline electrolyzer, LTPEMFC          | Ecoinvent 3.7.1                   | market for steel, unalloyed | steel, unalloyed | Cutoff, S - GLO |
| Lead          | Heat pump, marine engine                | Ecoinvent 3.7.1                   | market for lead | lead | Cutoff, S - GLO |
| Zinc          | Marine engine                          | Ecoinvent 3.7.1                   | market for zinc | zinc | Cutoff, S - GLO |
| Cast iron     | Marine engine, OCC, LTPEMFC             | Ecoinvent 3.7.1                   | market for cast iron | cast iron | Cutoff, S - GLO |
| Copper        | Heat pump, alternator, marine engine    | Ecoinvent 3.7.1                   | market for wire drawing, copper | wire drawing, copper | Cutoff, S - GLO |
| Aluminium     | Heat pump, alternator, marine engine, LTPEMFC | Ecoinvent 3.7.1 | market for aluminium, primary, ingot | aluminium, primary, ingot | CO2, S - IAI Area, EU27 & EFTA |
| Platinum      | LTPEMFC                                | Ecoinvent 3.7.1                   | market for platinum | platinum | Cutoff, S - GLO |
| Lanthanum     | SOFC                                   | Ecoinvent 3.7.1                   | market for lanthanum oxide | lanthanum oxide | Cutoff, S - GLO |
| Zirconia      | SOFC                                   | Ecoinvent 3.7.1                   | market for zirconium oxide | zirconium oxide | Cutoff, S - GLO |
| Yttria        | SOFC                                   | Ecoinvent 3.7.1                   | market for yttrium oxide | yttrium oxide | Cutoff, S - GLO |
| **Mineral and Ceramics** |                                   |                                   |                                                             |
| Titanium dioxide| SCR                                   | Ecoinvent 3.7.1                   | market for titanium dioxide | titanium dioxide | Cutoff, S - RER |
| Zinc oxide    | Methanol reformer, ammonia reformer     | Ecoinvent 3.7.1                   | market for zinc oxide | zinc oxide | Cutoff, S - GLO |
| Copper oxide  | Methanol reformer, ammonia reformer     | Ecoinvent 3.7.1                   | Copper oxide production | copper oxide | Cutoff, S - GLO |
| Alumina       | Methanol reformer, ammonia reformer     | Ecoinvent 3.7.1                   | market for aluminium oxide, metallurgical | aluminium oxide, metallurgical | Cutoff, EU27 & EFTA |
| Cobalt oxide  | SOFC                                   | Ecoinvent 3.7.1                   | market for cobalt oxide | cobalt oxide | Cutoff, S - GLO |
| **Other materials** |                                   |                                   |                                                             |
| De-ionised water| Electrolysis, Reformer operation, OCC operation | Ecoinvent 3.7.1 | market for water, deionised | water, deionised | Cutoff, S - Europe without Switzerland |
| MEA           | OCC operation, DAC operation           | Ecoinvent 3.7.1                   | market for monoethanolamine                                 |
| Sodium hydroxide| OCC operation                         | Ecoinvent 3.7.1                   | market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, S - GLO |
| Urea          | SCR operation                          | Ecoinvent 3.7.1                   | market for urea | urea | Cutoff, S - RER |
| Potassium hydroxide| Alkaline electrolysis               | Ecoinvent 3.7.1                   | potassium hydroxide production | potassium hydroxide | Cutoff, S |
| Carbon black  | LTPEMFC                                | Ecoinvent 3.7.1                   | market for carbon black | carbon black | Cutoff, S - GLO |
| Graphite      | LTPEMFC                                | Ecoinvent 3.7.1                   | market for anode, graphite, for lithium-ion battery | anode, graphite, for lithium-ion battery | Cutoff, S - GLO |
S3: Life cycle assessment result

S3.1 Environmental impact assessment

The pLCA results for different impact categories (other than GWP) without normalization at various life cycle phases are shown in Figures S4 to S12. Impact categories are assessed according to Environmental Footprint (EF) 3.0 LCIA method recommended by the European Commission’s Joint Research Centre.

Figure S5: pLCA results of different propulsion options for impact category acidification for the round trip.

Figure S6: pLCA results of different propulsion options for impact category freshwater ecotoxicity for the round trip.
Figure S7: pLCA results of different propulsion options for impact category marine eutrophication for the round trip.

Figure S8: pLCA results of different propulsion options for impact category terrestrial eutrophication for the round trip.

Figure S9: pLCA results of different propulsion options for impact category human toxicity, cancer effects for the round trip.
Figure S10: pLCA results of different propulsion options for impact category human toxicity, non-cancer effects for the round trip.

Figure S11: pLCA results of different propulsion options for impact category ozone depletion for the round trip.

Figure S12: pLCA results of different propulsion options for impact category particulate matter for the round trip.
S3.2 Scenario analysis

There are several possible configurations while designing and operating a B.E ship, three possibilities as listed in Table 5. Figure S13 shows the climate change impact (GWP20 and GWP 100) for these three scenarios. The main observations are: First, there is a significant difference in the GWP potential with different configurations and is mainly associated with the carbon intensity of electricity used. Second, the lowest GWP is for the configuration where the electricity comes from wind power with the battery storage infrastructure. This indicates that the port facility to store the electricity from renewables is promising for BE. Third, having onboard batteries for the round trip is better than having only for a single trip as it allows charging from cleaner electricity. In the case of b, the GWP is high due to the higher carbon intensity of the German mix. However, additional space and weight are required onboard for round trip considering the lower volumetric and gravimetric energy density of battery packs.

Figure S13: pLCA results of different propulsion options for impact category photochemical ozone formation for the round trip.

Figure S14: Climate change impact for different scenarios for BE option.
S3.3 Uncertainty analysis

The uncertainty ranges of the result based on the parameters listed in Table 5 of the main article for all the categories are shown in Figures S14 to S24 for the assessed decarbonized pathways. The same methodology is used for the assessment, that is IPCC AR6 for GWP and EF3.0 for other impact categories. The result shows that all options remain effective to reduce the GWPs, however, the uncertainty in the nitrous oxide emission makes eNH3ICE more uncertain.

Figure S15: Monte-Carlo simulation results of different propulsion options for impact category climate change GWP100.

Figure S16: Monte-Carlo simulation results of different propulsion options for impact category climate change GWP20.
Figure S17: Monte-Carlo simulation results of different propulsion options for impact category acidification for the round trip.

Figure S18: Monte-Carlo simulation results of different propulsion options for impact category freshwater ecotoxicity.

Figure S19: Monte-carlo simulation results of different propulsion options for impact category marine eutrophication.
Figure S20: Monte-Carlo simulation results of different propulsion options for impact category eutrophication terrestrial.

Figure S21: Monte-Carlo simulation results of different propulsion options for impact category human toxicity, cancer effect.

Figure S22: Monte-Carlo simulation results of different propulsion options for impact category human toxicity, non-cancer effect.
Figure S23: Monte-Carlo simulation results of different propulsion options for impact category ozone depletion.

Figure S24: Monte-Carlo simulation results of different propulsion options for impact category particulate matter.
S4: Life cycle cost results

S4.1 Fuel cost uncertainty

Most of the uncertainties considered in this study are linked to fuel production including the cost of the electricity, the energy required for different processes, the uncertainty in the investment cost, etc. For the eMeOH option, the recirculation of CO$_2$ captured onboard reduces the MeOH cost as the cost of capturing CO$_2$ from the DAC is expensive compared to other options. Figure S25 illustrates the result of uncertainty analysis for the cost of fuel.

Figure S25: Monte-Carlo simulation results of different propulsion options for impact category photochemical ozone formation.

S4.2 Uncertainty analysis with port infrastructure

The cost of distribution varies between the fuel, even though it is not added in the main analysis but is analyzed based on data shown in Table S13. Figure S26 illustrates the total eLCC results including fuel distribution cost, and the result shows that the eLH$_2$ options have the highest impact.

Figure S26: Cost of the fuel calculated and used for the calculation of LCC. The uncertainty range is based on the Monte-Carlo analysis.
of around 30% of the total cost, followed by BE options with 17% of the total cost. These have a significant change in the ranking of the options based on the cost.

Figure S27: eLCC results including the cost associated without the fuel distribution.

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