Electronic Supplementary Material (ESI) for Sustainable Energy & Fuels.
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The environmental performance of a fossil-free ship propulsion system with onboard carbon capture – a life cycle assessment of the HyMethShip concept

Electronic Supplementary Information

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Table S1. Summary of technology alternatives and fuel production route scenarios assessed in the life cycle assessment. The table includes notations of main data sources for each scenario. For further details on data presented in other tables.

Alternative scenarios	Propulsion technology	Maritime fuel	Physical state when entering combustion process	Fuel production pathway	Main data sources	
					Fuel	Engine
HyMethShip – baseline scenario	A dual fuel spark ignited ICE engine combined with areformer and a carbon capture system.	Electro-methanol	Liquid (MeOH)/ Gas (H2)	Renewable electro-methanol is produced using CO_2 from direct air capture, recycled CO_2, and hydrogen from water electrolysis produced with renewable electricity (wind power).	[1, 2]	Project measurements
CI ICE - MGO	Conventional compression ignited ICE optimized for diesel combustion	MGO	Liquid	MGO is produced from fossil sources in petroleum distillation	ELCD database 2.0 for fuel oil nb. 2 <0.1% Sulfur	[3]
CI ICE+SCR - MGO	Conventional compression ignited ICE optimized for diesel combustion combined with Selective Catalytic Reduction	MGO	Liquid	MGO is produced from fossil sources in petroleum distillation	ELCD database 2.0 for fuel oil nb. 2 <0.1% Sulfur	Calculations, [3]
ICE - eMeOH	Spark ignited ICE optimized for methanol combustion	Electro-methanol	Liquid	Renewable hydrogen and electro-methanol are produced through electrolysis based on renewable electricity (wind power) and direct air capture of CO_2.	[1, 2]	[4]
ICE - BioMeOH	Spark ignited ICE optimized for methanol combustion	Bio-methanol	Liquid	Biomethanol is produced through gasification of biomass (willow) into synthesis gas that is synthesized and processed	[5, 6]	[4]
ICE - NGMeOH	Spark ignited ICE optimized for methanol combustion	Fossil-methanol	Liquid	Fossil methanol is produced using natural gas as a raw material through a methanol synthesis.	[7]	[4]
CI ICE - NGMeOH	Compression ignition engine optimized for methanol combustion with MGO as pilot fuel	Fossil-methanol and MGO	Liquid	Fossil methanol is produced using natural gas as a raw material through a methanol synthesis. MGO is produced from fossil sources in petroleum distillation	[7, 8]	[9]

Table S2. Technical data for the case study vessel used in the assessment.

Vessel parameter	Value
Vessel type	RoPax Ferry (roll-on/roll-off passenger vessel)
Length	240 m
Beam	29 m
Draught	6.1 m
Lane meters	3,907m
Installed power	24 MW distributed on 4 main engines
Propulsion	2 × Controllable pitch propellers 3 × Bow thrusters
Capacity	51,837 GT
Top speed	21.5 knots

1. Life cycle inventory: unit data processes

Table S3. Unit processes used for modelling of electro-methanol production.

	Flow properties	**Amount**	**Unit**	**Reference**
Water electrolyzer, alkaline electrolyzer				
Reference flow				
hydrogen, gaseous	Product	1	kg	van der Giesen, Kleijn and Kramer [10]
Inflows				
de-ionized water	Product	11.1	kg	van der Giesen, Kleijn and Kramer [10]
potassium hydroxide	Product	0.000475	kg	Adapted from KOH solution values in Koj et al[11]
electricity	Product	57.618	kWh	van der Giesen, Kleijn and Kramer [10], adjusted with additional compression to 35 bar (includes direct electricity and electricity required to run electric boiler)
Carbon dioxide capture, direct air capture				
Reference flow				
carbon dioxide, gaseous	Product	1	kg	van der Giesen, Kleijn, and Kramer [10]
Inflow				
electricity	Product	1.1	MJ	van der Giesen, Kleijn, and Kramer [10]
Methanol synthesis for direct hydrogenization				
Reference flow				
Methanol, at plant	Product	1	kg	Kiss et al [1]
Inflow				
carbon dioxide, gaseous	Product	1.376	kg	Kiss et al [1]
hydrogen, gaseous	Product	0.189	kg	Kiss et al [1]
electricity	Product	5.237	MJ	Kiss et al [1]
Outflow				
Carbon dioxide	Emissions to air	7.65E-6	kg	Kiss et al [1]
Carbon monoxide	Emissions to air	6.9E-7	kg	Kiss et al [1]
Hydrogen	Emissions to air	1.13028E-4	kg	Kiss et al [1]
Methanol	Emissions to air	0.00172	kg	Kiss et al [1]
Water	Emissions to air	0.58659	kg	Kiss et al [1]

Table S4. Unit processes for the HyMethShip engine system. The processes are designed to represent a circular flow of carbon, where new electro-methanol is produced using the recycled carbon stream. Parameters for calculations noted in parentheses after the parameter name.

	Flow properties	**Amount**	**Unit**	**Reference**
HyMethShip, bunkering - Parameter driven model process. Equations defined in parenthesis after the parameter.				
Reference flow				
methanol, bunkered	Product	1	kg	Parameter driven model process. Equations defined in parenthesis after the parameter.
Inflow				
Methanol, at plant	Product	MeOH_DAC (=0.726744186*p_1)		Amount of methanol produced using DAC
Hydrogen, gaseous	Product	H2_reCO2 (= 0.137478198*(1.235 - p_1))		Used to model circular flow of carbon dioxide i.e. required to produce new electromethanol from recycled CO_2
Methanol synthesis process without inflows	Product	MeOH_reCO2 (= 0.726744186*(1.235-p_1))		Used to model circular flow of carbon dioxide i.e. required to produce new electromethanol from recycled CO_2
Outflow				
Carbon dioxide	Emission to air	p_1 (0.0247, which represent 2% CO_2 loss)		Share off CO_2 lost in the system. Fixed for base case analysis, varied in Monte Carlo Analysis. Range from P_1=0.00617 to P_1=0.0617
HyMethShip, Traveling at speed with Hydrogen				
Reference flow				
propulsion, high engine load	Product	1	kWh	
Inflow				
Methanol, bunkered onboard ship	Product	361	g	Process used in model calculations which acts as a proxy for the bunkering requirements on the vessel. This unit process combines activity by both reformer and engine. In to one calculation
De-ionised water	Product	0.4219	kg	Project calculations and measurements
Outflow				
Ammonia	Emission to air	0	g	Project calculations and measurements
Carbon dioxide	Emission to air	0	g	Project calculations and measurements
Carbon monoxide	Emission to air	0.1285	g	Project calculations and measurements
Formaldehyde	Emission to air	0.014	g	Project calculations and measurements
Methane	Emission to air	0	g	Project calculations and measurements
Nitrogen oxides	Emission to air	0.784	g	Project calculations and measurements
NMVOC	Emission to air	0.00283	g	Project calculations and measurements
Particulates, < 10 um	Emission to air	0.0213	g	Project calculations and measurements
Sulphur oxides (as SO_2)	Emission to air	0	g	Project calculations and measurements
HyMethShip, Maneuvering with Hydrogen				
Reference flow				
propulsion, low engine load	Product	1	kWh	
Inflow				
Methanol, bunkered onboard ship	Product	8.05	MJ	Model tool for model calculations. Driver from bunkering process. This unit process contains activity by both reformer and engine.
De-ionised water	Product	0.45436	kg	Project calculations and measurements
Outflow				
Ammonia	Emission to air	0	g	Project calculations and measurements
Carbon dioxide	Emission to air	0	g	Project calculations and measurements
Carbon monoxide	Emission to air	0.0037	g	Project calculations and measurements
Formaldehyde	Emission to air	0.0119	g	Project calculations and measurements
Methane	Emission to air	0	g	Project calculations and measurements
Nitrogen oxides	Emission to air	1.589	g	Project calculations and measurements

NMVOC	Emission to air	0	g	Project calculations and measurements
Particulates, < 10 um	Emission to air	0.0126	g	Project calculations and measurements
Sulphur oxides (as SO_2)	Emission to air	0	g	Project calculations and measurements
HyMethShip, Methanol back up system				
Reference flow				
propulsion, backup system	Product	1	kWh	
Inflow				
Methanol	Product	501	g	
Outflow				
Ammonia	Emission to air	0	g	Project calculations and measurements
Carbon dioxide	Emission to air	697	g	Project calculations and measurements
Carbon monoxide	Emission to air	10.7	g	Project calculations and measurements
Formaldehyde	Emission to air	0.27	g	Project calculations and measurements
Methane	Emission to air	0	g	Project calculations and measurements
Nitrogen oxides	Emission to air	1.78	g	Project calculations and measurements
NMVOC	Emission to air	0.843	g	Project calculations and measurements
Particulates, < 10 um	Emission to air	0.17	g	Project calculations and measurements
Sulphur oxides (as SO_2)	Emission to air	0	g	Project calculations and measurements
HyMethShip, Case Study Vessel Trip				
Reference flow				
Trip with vessel	Functional unit	1	Unit	Functional unit of this study
Inflow				
electricity mix	Product	16740.0	kWh	Industry data, cumulative data presentation based on detailed data set
propulsion, backup system	Product	5596.5	kWh	Industry data, cumulative data presentation based on detailed data set
propulsion, low engine load	Product	33529.5	kWh	Industry data, cumulative data presentation based on detailed data set
propulsion, high engine load	Product	382424.0	kWh	Industry data, cumulative data presentation based on detailed data set

Table S5. System process for Urea production.

	Flow properties	**Amount**	**Unit**	**Reference**
Urea production				
Reference flow				
Urea	Product	1	kg	
Outflows				
Ammonia	Emission to air	0.0016	kg	Winnes et al [12]
Carbon dioxide	Emission to air	1.8	kg	Winnes et al [12]
Carbon monoxide	Emission to air	0.00073	kg	Winnes et al [12]
Methane	Emission to air	0.002	kg	Winnes et al [12]
Nitrogen oxides	Emission to air	0.00327	kg	Winnes et al [12]
NMVOC	Emission to air	0.0016	kg	Winnes et al [12]
Particulates, < 10 um	Emission to air	0.00067	kg	Winnes et al [12]
Sulphur oxides (as SO_2)	Emission to air	0.0044	kg	Winnes et al [12]

Table S6. System processes used as background data in the life cycle assessment i.e. secondary data not fully investigated within the analysis of this study. This list includes background processes used in the main analysis, for details on sensitivity analysis see the sensitivity chapter in the main article.

	Flow properties	**Amount**	**Unit**	**Comment**
Electricity production from wind power – detailed data presented in reference				
Reference flow				
	Product	1	kWh	NEEDS, [2] “1990 kW Offshore wind power plant”
Water production - detailed data presented in reference				
Reference flow				
de-ionized water	Product	1	kg	ELCD database 2.0,[8] “De-ionised water, production mix, at plant, reverse osmosis, from groundwater”
Electricity mix used for hotel load - detailed data presented in reference				
Reference flow				
electricity mix	Product	1	kWh	NEEDS, [2] “1990 kW Offshore wind power plant
Potassium hydroxide production - detailed data presented in reference				
Reference flow				
potassium hydroxide	Product	1	kg	Ecoinvent 3.7.1, “potassium hydroxide production | potassium hydroxide | Cutoff, S” original data source: http://esu-services.ch/fileadmin/ download/publicLCI/jungbluth-2007-17_Bioenergy.pdf
Transport, lorry 32t - detailed data presented in reference				
Reference flow				
transport, lorry 32t - RER	Product	1	t*km	NEEDS, [2] Included in NEEDS original file: today_transport_lorry_32t_RER_[tkm].xml
Marine gas oil production - detailed data presented in reference				
Reference flow				
MGO, 0.1 wt.% Sulphur	Product	1	kg	ELCD database 2.0,[8] “Light fuel oil at refinery, production mix, at refinery, from crude oil, fuel supply, 0.1 wt.% Sulphur”

2. Sensitivity analysis results

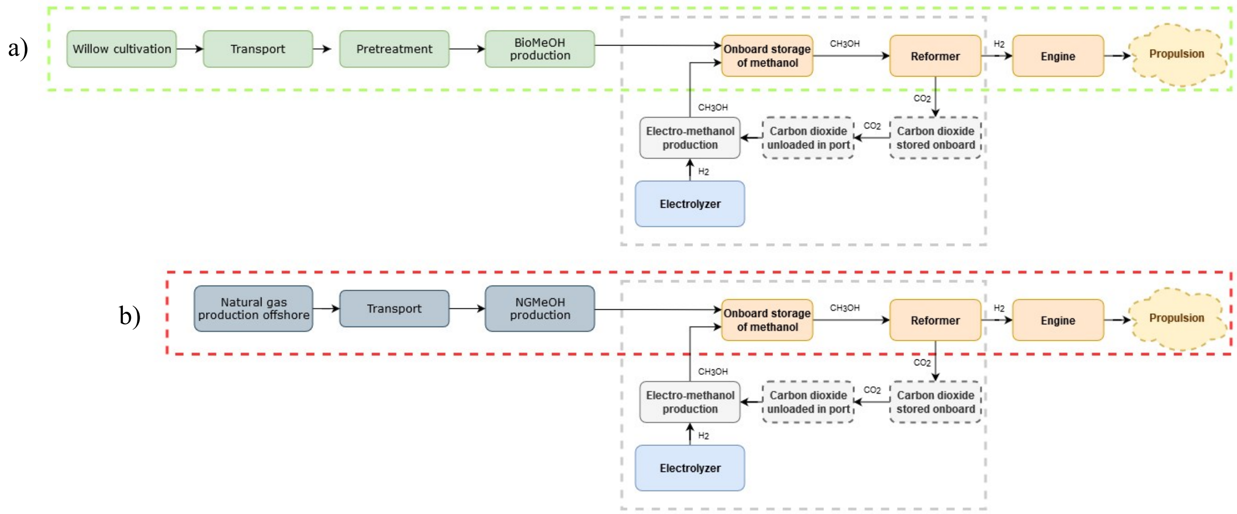


Fig. S1 Life cycle outline of two alternative fuel pathways used in the HyMethShip concept in the sensitivity analysis. Figure S1a shows a scenario where the HyMethShip system is combined with BioMeOH. Figure S1b shows a scenario where HyMethShip is combined with NGMeOH. The orange colored processes take place on the vessel. The green are processes related to BioMeOH production. The dark grey processes are processes related to NGMeOH production. Schematic presentation; Detailed life cycle is not outlined.

Table S7. Technology and data summary for alternative fuel HyMethShip concept scenarios used to investigate the influence of fuel production pathway.

Alternative scenarios	Propulsion technology	Marine fuel	Physical state when entering combustion process	Summary of assumed process	Main data sources
HyMethShip using eMeOH	A dual fuel spark ignited ICE engine combined with the HyMethShip concept	Electro-methanol	Liquid (MeOH)/ Gas (H2)	The HyMethShip concept base scenario. Renewable hydrogen and electro-methanol are produced through electrolysis based on renewable electricity (wind power) and direct air capture of CO_2.	[1], [13]
HyMethShip using bioMeOH	A dual fuel spark ignited ICE engine combined with the HyMethShip concept	Bio-methanol	Liquid (MeOH)/ Gas (H2)	Bio-methanol is produced by using willow as a biomass feedstock. CO2 captured by the HyMethShip system is used to produced electro-methanol through electrolysis based on renewable electricity (wind power).	[14], [1], [13]
HyMethShip using NGMeOH	A dual fuel spark ignited ICE engine combined with the HyMethShip concept	Fossil-methanol	Liquid (MeOH)/ Gas (H2)	Fossil methanol is produced using natural gas as a raw material through a methanol synthesis. CO2 captured by the HyMethShip system is used to produced electro-methanol through electrolysis based on renewable electricity (wind power).	[7]

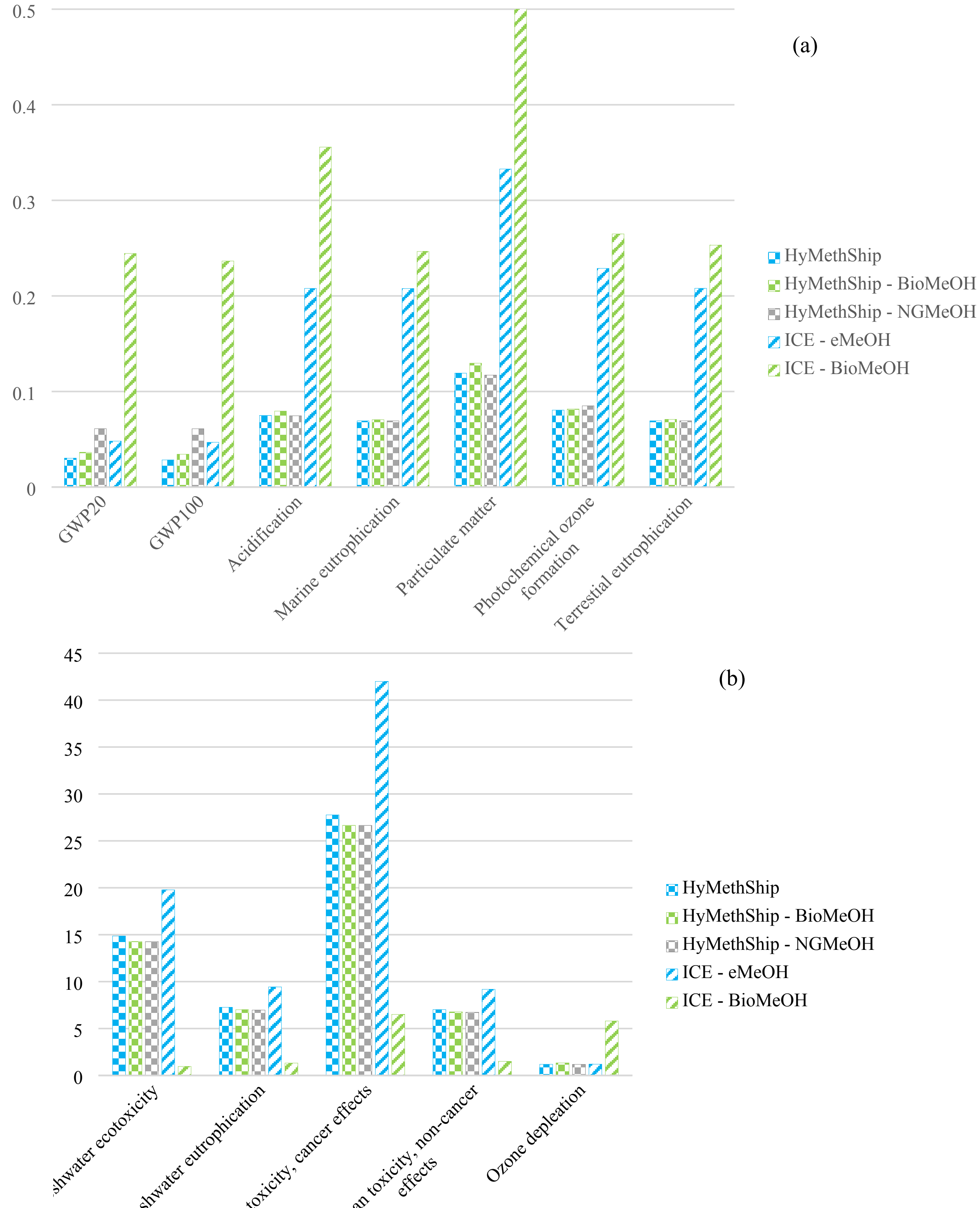


Fig. S2 Results from sensitivity analysis of various fuel production pathways combined with the HyMethShip system. Presented per round trip between Gothenburg and Kiel on a RoPax vessel and impact categories are normalized per CI ICE using MGO. (a) impact categories where HyMeth perform better than ICE – MGO; (b) impact categories where the HyMethShip concept has a higher environmental impact than ICE - MGO

As this life cycle study in part forecasts the future technology development within the shipping sector a Monte Carlo simulation of the main uncertainties can be viewed as giving insight to what is likely future outcomes. Based on technology progress all scenarios as well as scenarios outside of what is predicted here can occur, as the world can develop in ways which is today deemed as empirically unlikely (and outside the estimated ranges in scientific literature). The results of this assessment should be not viewed as absolute and the results considered as strictly dependent on the assumptions made by the authors, as is customary for LCA studies [15].

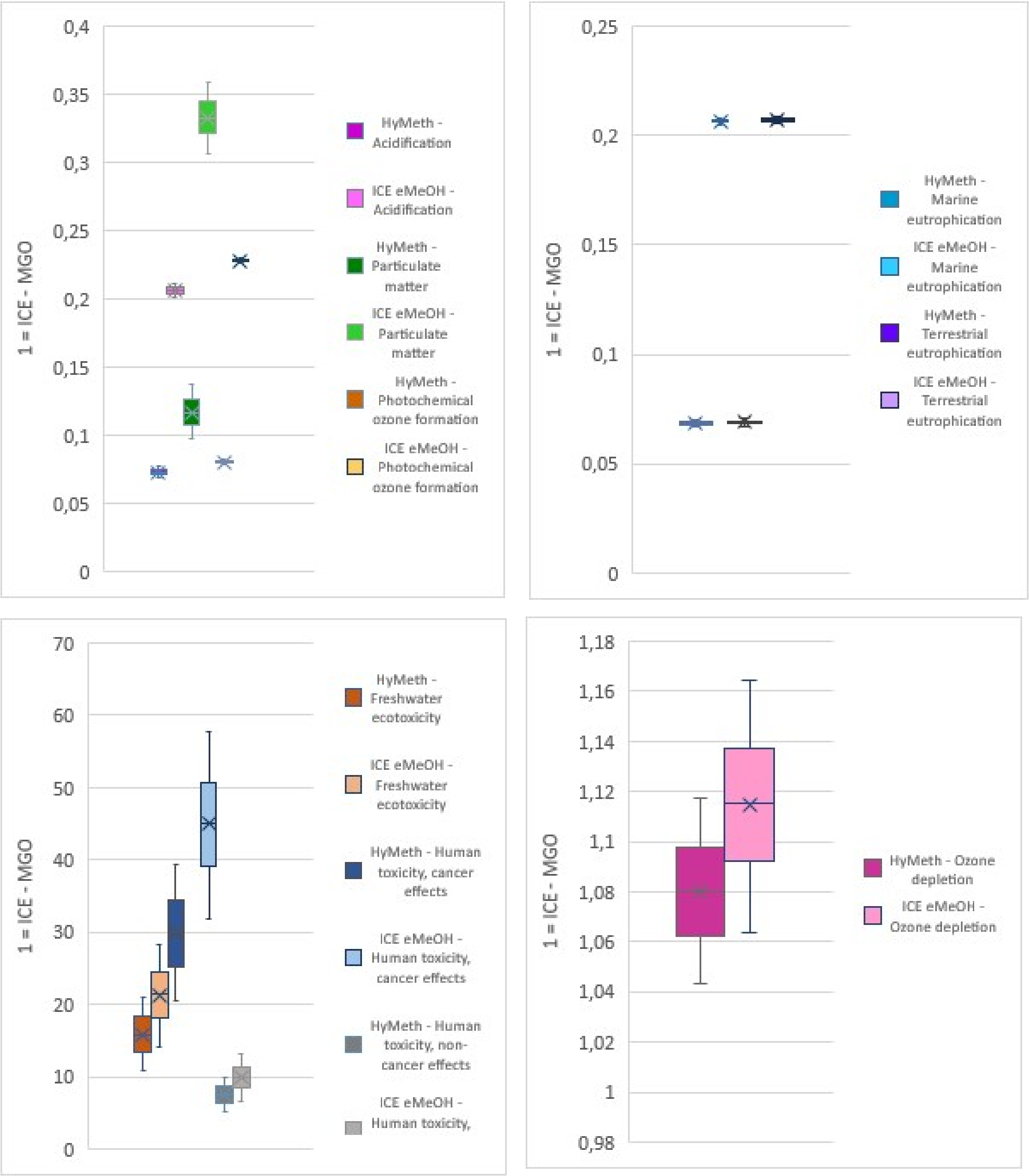


Fig. S3 Monte Carlo analysis of some technical uncertainties in future development of the HyMethShip onboard technology.

3. Detailed outline of the life cycle for the HyMethShip concept

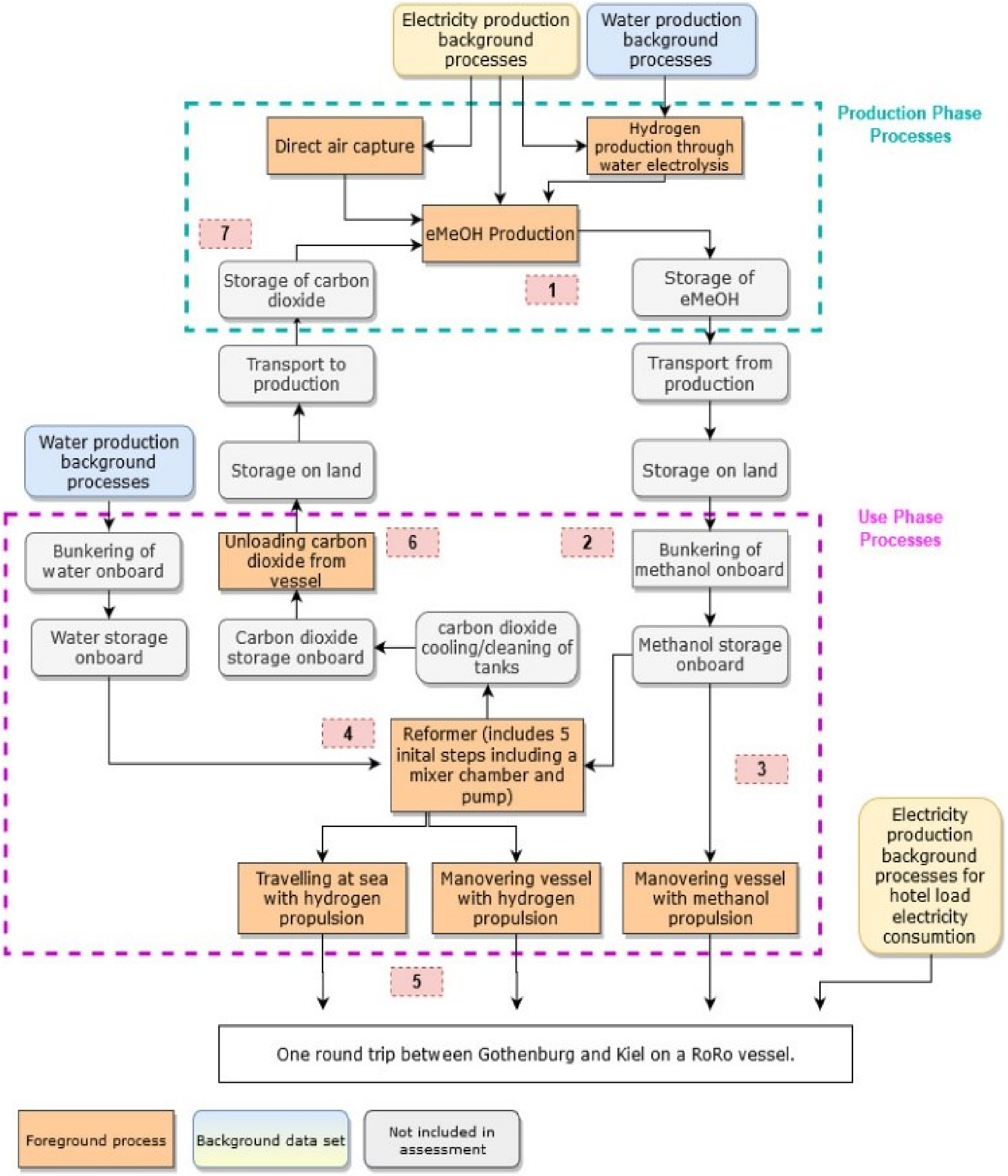
In **Error! Reference source not found.** a full schematic over processes included in the LCA of the HyMethShip concept is presented. In step [1] electro-methanol is produced using CO_2 from direct air capture and hydrogen from water electrolysis. The methanol is stored at the production facility and then transported to the harbor where it is stored until utilized. The methanol is bunkered and stored onboard the vessel [2]. There are no known losses connected to bunkering liquid fuels in ambient pressure under standard procedure, therefore this process is not included in the LCA. From the methanol storage two paths are possible, either the engine can be run on methanol directly [3] or the methanol is pumped to the reformer [4]. In the reformer the methanol is together with water converted into hydrogen and CO_2. The hydrogen is utilized to propel the vessel [5]. The CO_2 is cooled until liquefied and stored onboard. When in port the liquid CO_2 is unloaded [6] and stored until it can be transported to the electro-methanol production facilities. In the unloading process an estimated 2% of the liquefied CO_2 is lost as emissions to the atmosphere. The captured CO_2 is then used to replace CO_2 from direct air capture in the electro-methanol production [7].

Fig. S4 Detailed outline of the HyMethShip concepts life cycle focusing on the production phase process and use phase process. The carbon chain is accounted for using a circular carbon flow. Transport of fuel and liquified CO2, bunkering of water and methanol, and storage of methanol and water are all assumed to lead to negligible energy consumption and emissions. The cyan colored line shows processes related to the production phase (Section 3.2) and the magenta boundary shows the processes related to the use phase of the vessel (Section 3.3).

4. Hotel load at Anchour

The hotel load in the Gothenburg harbor is currently provided to the vessel by shore power and this assumed to continue. Swedish electricity grid is assumed for the shore power. The hotel load in Kiel harbor is maintained by the onboard ICE system. Major changes to the harbor infrastructure would be required for the vessel to connect to the German electricity grid and for this assessment it is therefore assumed this will remain the case for 2030.

5. Electromethanol production



In this study we consider methanol produced using water and carbon dioxide as outlined in Figure 2. First water is used in an electrolysis process, where electricity is used to split water into hydrogen and oxygen. The hydrogen is then used in a methanol synthesis together with carbon dioxide producing electro-methanol. All heat used to produce electro-methanol are assumed to come from electric heating and all electricity is assumed to be offshore wind power with a data set from Denmark (1990 kWh facility).

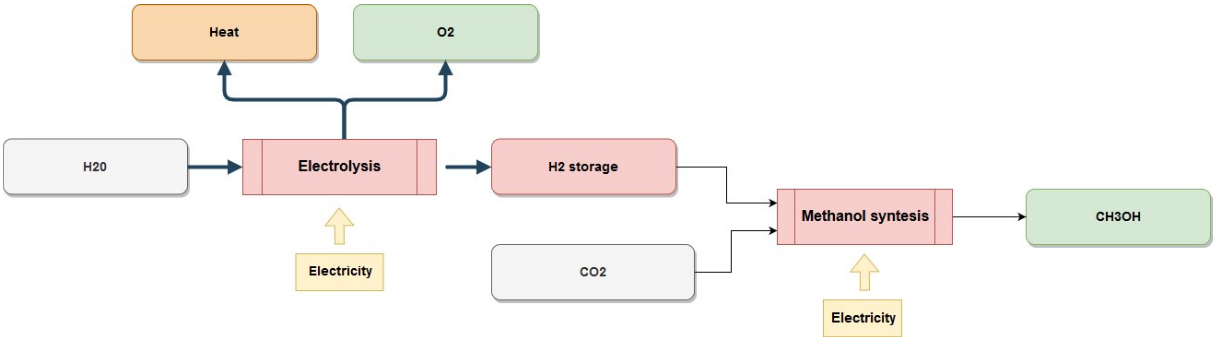


Fig. S5 Simplified schematic of the electromethanol production process. Red boxes indicate processes which a methanol producer is in control of (i.e. foreground processes for the methanol producer). Grey boxes indicate material inflows to the production. Green boxes indicate material outflows from the production. Yellow boxes indicate energy-based inflows. Orange box shows energy-based outflow.

5.1. Direct air capture

The CO_2 is provided through captured CO_2 from the HyMethShip system and a direct air capture process (DAC). DAC is used for the CO_2 needed to at first fill the vessel with and any additional CO_2 required to meet the demands from the ship e.g. to balance out losses in the otherwise closed system. Air capture is one of the considered options for reducing global atmospheric CO_2 concentrations as a route to manage global warming[16]. The data used in the base case is based on a moister swing with a solid resin which releases CO_2 at a temperature of 45 degrees. The process used in this work is based on a theoretical calculation/process as presented by Klaus Lackner [10]. All the heat that is needed will be produced as an incidental by-product of the compressor (Song et al., 2019). In total 50 kJ/mol CO_2 or 1.1 MJ (= 0.31 kWh) electrical energy/kg CO_2 is needed [10]. The material requirements for the units are not included in this assessment. One of these units should be able to collect 1 ton of CO_2 per day.

5.2. Electrolyzers

The hydrogen is produced through water electrolysis. Only a minor portion of today's hydrogen production is based on electrolysis [17], but this is a fossil free option for hydrogen production if combined with low carbon electricity in contrast to steam reforming which is the most commonly used technology today. The hydrogen production has three stages in principle: Plant manufacturing and installation (not included here), plant operation and storage/delivery [18]. The production is assumed to be done on-site, limiting the need for transport and storage of hydrogen. The water used is assumed to be de-ionized water from ground water sources.

The production of 1 kg of hydrogen requires 11 kg of water and uses 56.7 kWh of electricity [10]. An additional amount of 0.918 kWh electricity is needed to compress the hydrogen to 35 bar, which is needed for the downstream processes. Main products are: H2, O2, heat. Only hydrogen is used in this analysis. A review over life cycle assessments done on electrolyzing processes written by Bhandari et al [18] notes the specific energy consumption of an alkaline electrolyzers is between 54-84 kWh/kg hydrogen (4.5 and 7.0 kWh/Nm3 hydrogen). The above stated electrolysis process is thereby in the lower range.

For the combination of renewable energies with hydrogen production, the proton exchange membrane electrolyzer may be preferable since it reacts quickly, and fluctuations effect the electrolyte to a low degree [19]. However, it has a high investment cost compared to alkaline electrolyzers and are still in the development phase. The emission data used in this report is based on an alkaline electrolyte, the most evolved and widely used water electrolyzing process as of today.

5.3. Methanol synthesis for electro-methanol

In this study, only one electro-methanol production route is considered, as described earlier. The methanol synthesis process is based on theoretical calculations and computer simulation as presented by [1]. In this study, the production uses captured CO_2 from the ship and electricity derived from wind power plants making the methanol renewable and closing the CO_2 loop.

The process requires carbon dioxide (1.375 kg/kg MeOH), hydrogen (0.189 kg/kg MeOH), electricity (1.98 MJ/kg MeOH), and heat. The heat is provided through electric heating for the base case it is assumed that no heat is reused, leading to a total electricity consumption of 5,24 MJ/kg MeOH. Literature sources presenting methanol synthesis simulations for direct hydrogenization mainly differs in figures given for the amount of steam/heat required in the process, with variations from almost no heat required up to 10 times the figures given in Kiss et al [1].

There is an alternative route to this where the carbon dioxide first is converted into carbon monoxide in a reverse water gas shift reaction (RWGS). The carbon monoxide is then combined with the hydrogen creating syngas before the methanol synthesis. This process alternative, sometimes referred to as indirect hydrogenization or a two-step conversion, falls within the stated definition but will not be assessed in this paper. Comparisons between the two routes can be found in Anicic et al. [20].

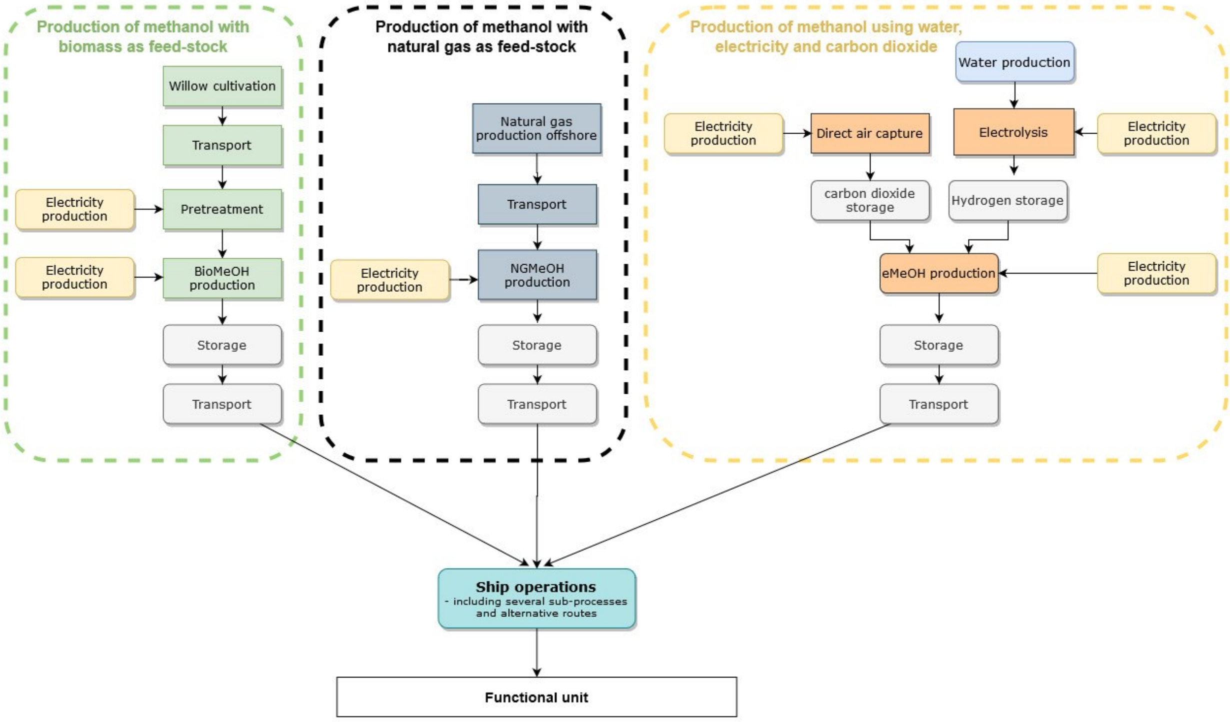


Fig. S6 Simplified schematic over investigated methanol production routes from different feedstock for a return trip from Gothenburg to Kiel with a roro vessel. Background processes are included and marked with yellow and light blue.

6. Methanol from biomass

The methanol produced from biomass comes from data regarding methanol from willow production (see green boxes in Figure 1). The willow is grown in Sweden and four major processes are included: collection of willow, transportation, pre-treatment and the methanol synthesis. The methanol synthesis goes via syngas and the pre-treatment process only uses electricity to dry the biomass. The first two processes are based on data presented by Börjesson [14] in combination with [21]. The study was originally made on LCA of willow production with the geographical boundary of Sweden. The two later processes are based on [22] and [5].

6.1. Collection of willow

This process contains aggregated data for refers the processes of establishment, recovery, fertilization and harvest of 1 MJ willow collected in southern Sweden. Thereby it includes various agricultural practices such as ploughing, planting, etc. These processes are done using fossil energy sources and the state-of-the-art technology for 2005, which includes commercial fertilizers. When the willow grows carbon is captured and fixated in the biomass. The amount of carbon captured in this way is quantified based on estimations of carbon content in willow grown in southern Sweden as presented by [21]. This carbon is assumed to enter the system boundary from the atmosphere. The carbon content is estimated to 490 mg per g willow. LVH for willow is given as 16.5 GJ per ton willow. The amount of CO_2 captured per MJ of willow is given by:

$$C_{captured} = \frac{44}{12} \times \left(\frac{1}{LVH_W} \times C_W \right)$$

Where:

$C_{captured}$	is amount of CO_2 captured per MJ of willow (kg/MJ)
LVH_W	is the lower heating value for willow (MJ/kg)
C_W	is the carbon content per kg of willow (kg/kg)

As given by the above equation and estimated values 0.109 kg CO_2 is captured per MJ willow.

6.2. Transportation of willow

This process refers to the unit process of transportation of 1 MJ willow to a facility where it is further treated to produce methanol. Transport distance is assumed to be an average of 30 km one way. Energy consumption for this transport includes empty backhaul [14].

6.3. Pretreatment of willow

This process contains energy consumption data. By using electricity at the facility, the willow is pre-heated to remove most of the moisture content. This is done to prepare the material so that it can be converted into syngas. No direct emissions are included in this process. The data used comes originally from Procter and Gamble Technical centers but has been extracted from [22] in [23] and refers to 1 MJ willow as output with gate-to-gate system boundary. The data was gathered from 1992 till 2001. The electricity used is from the NEEDs projects realistic future scenario for 2025[2]. The NEEDs database contains life cycle inventories on future transport services, electricity, and material supply as well as reference inventory data for today's corresponding technologies.

6.4. Methanol synthesis via syngas

The methanol synthesis is applicable to generic biomass, and concerns gate-to-gate for 1 MJ of methanol. The data is originally based on an alternative fuels study from Chalmers University of Technology and was here collected from [5]. The biomass is first dried and preheated before it is gasified in two steps: partial oxidation and pyrolysis. The produced synthesis gas is then cleaned and compressed to approximately 60 bar. This synthesis gas is fed to the methanol rector. The oxygen used for the partial oxidation is retrieved from the air though a distillation process. The electricity used is assumed to be a grid mix and is from the NEEDs projects realistic future scenario for 2025. Ash produced in the process is assumed to contain any additional carbon not emitted as air emissions or remaining the produced methanol. The ash is assumed to be distributed to the air over time.

7. Methanol from natural gas

The natural gas production and treatment data is based on Norwegian offshore production and the methanol synthesis is based on steam reformation of fossil natural gas. The fossil methanol case includes five main processes: natural gas drying, sweet gas burned in gas turbines, diesel burned in diesel electric generating set, flaring and methanol synthesis.

7.1. Diesel burned in diesel electric generating set

For the electricity production diesel-electric generating sets are used during the natural gas extraction. The data used in this work is from GEMIS 4.8.1 (2013) and represents a larger-scale diesel motor for electricity production without any emission control.

7.2. Sweet gas burned in gas turbines

Energy is needed in several different processes to produce natural gas. The energy requirements to produce natural gas, both in the direct production and in the processing of the product, is meet by using some of the natural gas to create energy. It is here assumed that gas turbines, gas boilers and gas motors are used for this. The emissions data is mainly based on the Norwegian Environmental Report (OLF, 2011) and documented by Schori, Frischknech [7].

7.3. Flaring

For technical and commercial reasons not all gas is utilized in the production. The unutilized gas is burden under controlled conditions to be removed, so called flaring. Flaring of gas is also used as a safety measure during, start-up maintenance or stops in the normal processing and production operations. The emissions data is for this process mainly based on the Norwegian Environmental Report (OLF, 2011) and documented by Schori, Frischknecht [7]

7.4. Natural gas drying

Data on emissions to air are taken from Statoil (2001) and documented by Schori, Frischknecht[7]. The basis for modelling natural gas drying is the processing plants Kollsnes and Kårsø. Around 60% of the natural gas in Norway is produced here. The raw gas is heated up and distilled into various components. The emission data include flaring and combustion of energy carriers.

7.5. Methanol production process with natural gas as raw material

The fossil methanol production scenario is based on steam reformation of fossil natural gas. This is the most common and lowest cost production method of fossil methanol that is available in Europe today. The emission and process data for production of methanol were taken from Strömman et al. [24], which assumed production of methanol in Norway from Norwegian natural gas, and transport of the methanol by chemical tanker a distance of 350 nautical miles (NM). The process is highly endothermic, and heat needs to be supplied to the system. This is usually done by burning a part of the natural gas used as feedstock

8. Normalized results

Normalization can give an indication of the relationship between impacts in different impact categories by relating them to quantities we understand[25]. The normalization used in the main paper simply gives an indication of the comparison between the alternatives and does not say anything about the size of the individual impact in relation to the environmental effects they cause in the natural systems. There are three further recommended normalization methods in ILCD[26] and figures S7-S9 below present the results normalized on these principles (emissions emitted per year in different capacities). As can be seen some categories appears to be of lower importance than others, but not direct conclusion about the toxicity related impacts can be drawn, as human toxicity cancer effects are in the higher range of all impact but the HyMethShip results are still lower than for some of the other options. The normalization methodology is full of uncertainties, but it gives an indication that the trade.-off identified in this paper might not be neglectable and requires further investigation.

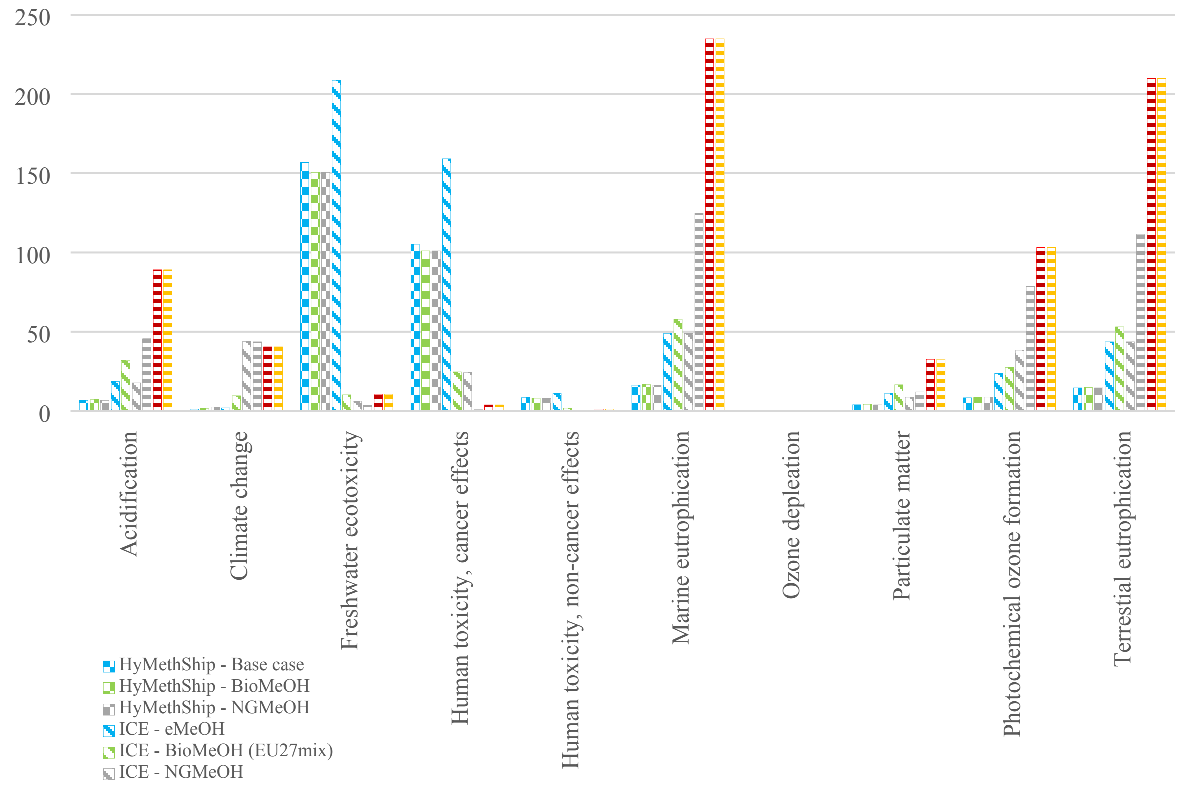


Fig. S7 Results from life cycle assessment normalized per persons average emissions per year according to prosuite global. Y-axis represents the relationship to the prosuite global value.

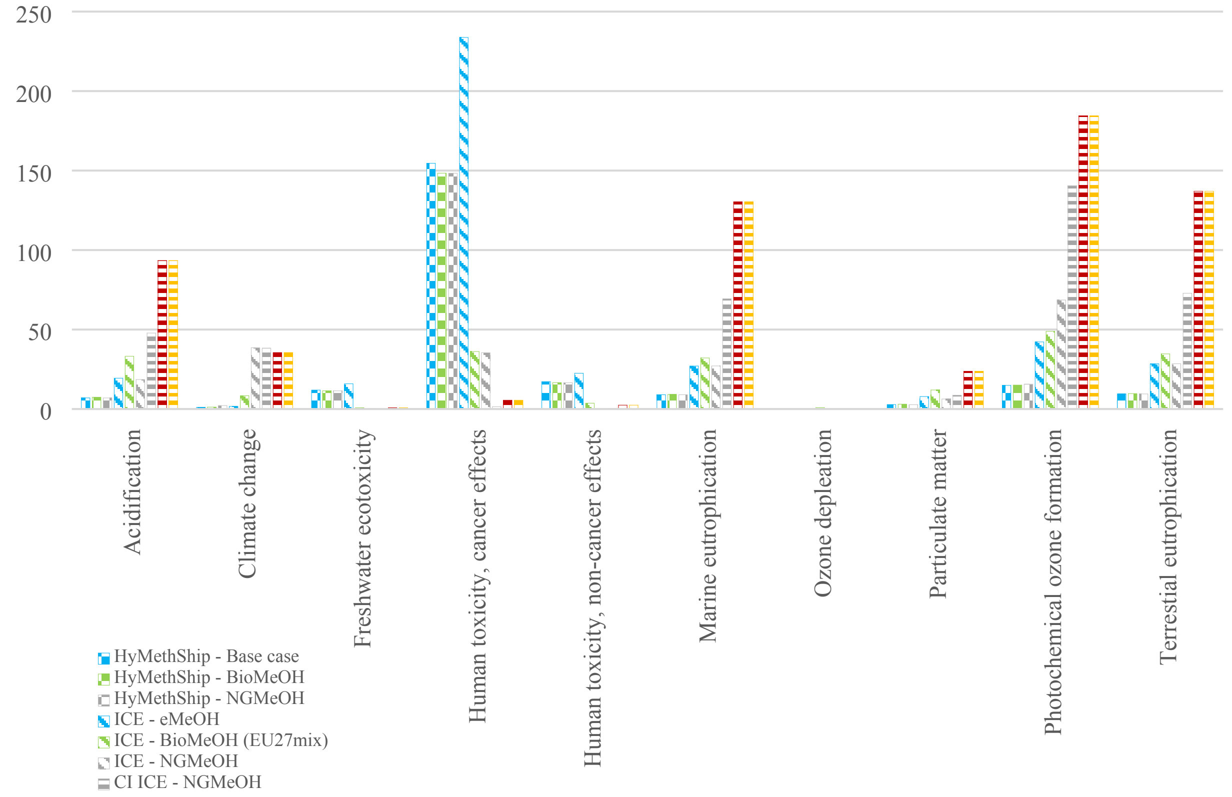


Fig. S8 Results from life cycle assessment normalized per persons average emissions per year according to EC-JRC EU27 from 2010. Y-axis represents the relationship to the EC-JRC EU27 value.

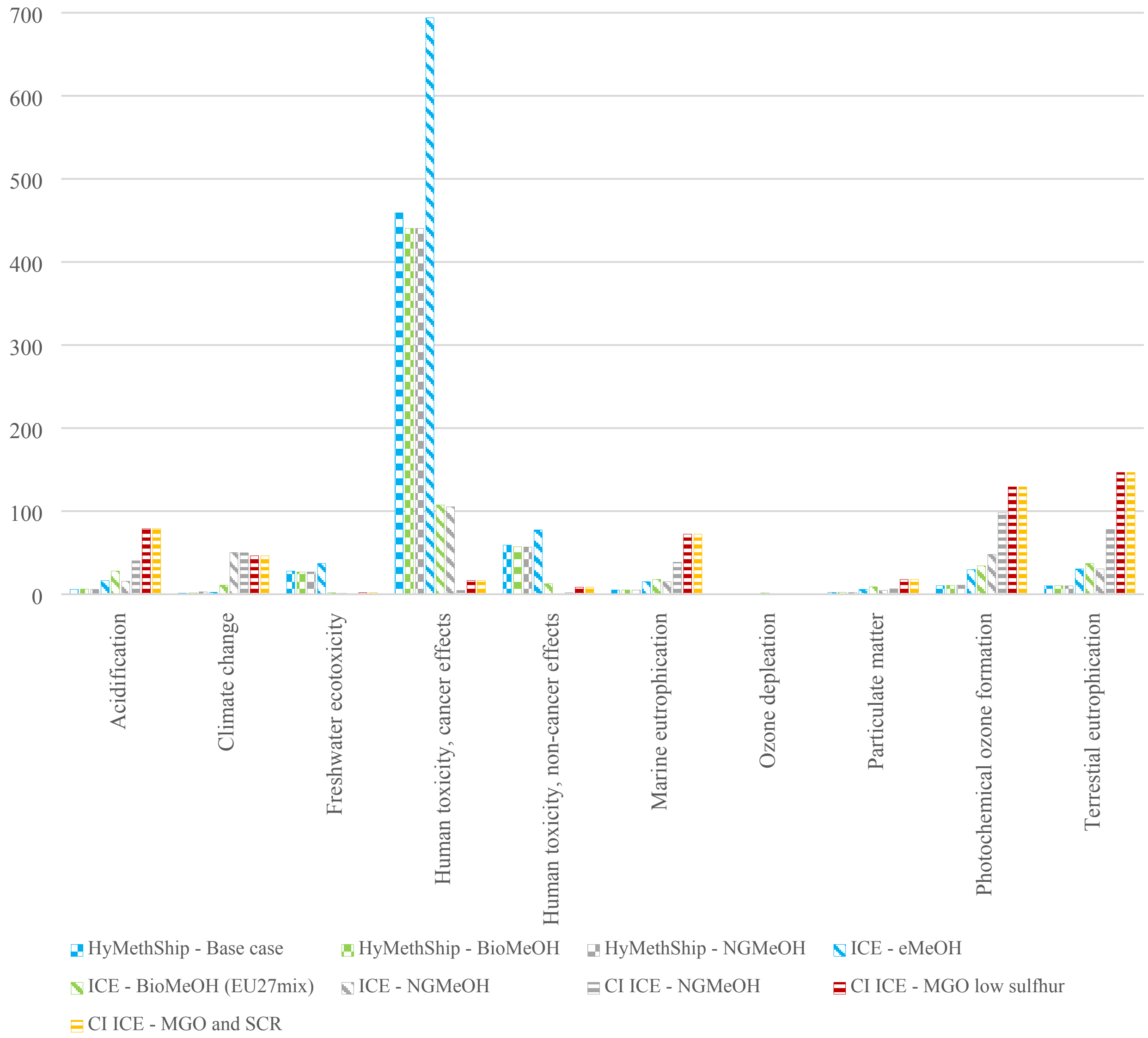


Fig. S9 Results from life cycle assessment normalized per persons average emissions per year according to EC-JRC Global from 2013. Y-axis represents the relationship to the EC-JRC Global value

9. Metal emissions effect on toxicity

Exhaust gas emissions from fuel oil combustion are known to contain metal emissions [27]. These emissions have not been included in this LCA and could impact the results, unlike metal emissions occurring in the fuel production. Some numbers are available on the mental emissions from combustion MGO and to give an indication of how including metal emissions could impact the results of this study a comparison has been made where exhaust gas emissions from MGO has been included in emissions from the CI ICE – MGO scenarios. This scenario where metal emissions are added is labeled “CI ICE – MGO and Metals” in figure 6 of this ESI.

The emissions of metals when combusting MGO in a vessel has been estimated to reach between 0.0002-0.8 g/kWh engine power [27], depending on metal and engine load. When adding these emissions to the life cycle inventory (including them in the assessment performed in this study) we can see that the impact on toxicity related categories increases compared to when they are not included (see Fig. S10 Relative impact between Marine Gas Oil propulsion when metal emissions from fuel combustion is not included (red) and included (purple). Metal emission estimations from Agrawal et al [27]

11. Results from all life cycle assessment scenarios without normalization

Table S8. Life cycle assessment results for all scenarios.

Impact category	unit	HyMethShip - Base case	HyMethShip - BioMeOH	HyMethShip - NGMeOH	ICE - eMeOH	ICE - BioMeOH	ICE - NGMeOH	CI ICE - NGMeOH	ICE - MGO	CI ICE - MGO +SCR	CI ICE - MGO and Metals
GWP20	kg Co2 eq.	10387	12510	21056	16574	84258	356619	356953	344752	354605	344752
GWP100	kg Co2 eq.	9300	11249	19975	15343	77461	355565	353331	327493	337345	327493
Acidification	molc H+ eq.	331	351	330	919	1572	878	2262	4419	1125	4419
Climate change	kg Co2 eq.	9404	11339	20071	15495		355466	353001	325973	335644	325973
Freshwater ecotoxicity	CTUe	104258	100116	100032	138771	6761	4099	2250	7016	7016	108974
Freshwater eutrophication	kg P eq	0,361	0,348	0,346	0,469	0,066	0,004	0,010	0,050	0,050	0,050
Human toxicity, cancer effects	CTUh	0,006	0,005	0,005	0,009	0,001	0,001	0,000	0,000	0,000	0,000
Human toxicity, non-cancer effects	CTUh	0,009	0,009	0,009	0,012	0,002	0,000	0,000	0,001	0,001	0,005
Ionizing radiation	kBq U235 eq.	0,048	0,053	0,047	0,048	0,227	0,038	0,039	0,044	0,044	0,044
Ionizing radiation E (interim)	CTUe	5692	6225	5625	6036	23022	3886	3932	4240	4240	4240
Land use	kg C deficit	16869	16175	16266	22121	0	2922	2632	566	566	566
Marine eutrophication	kg N eq.	153	155	153	457	543	458	1171	2203	465	2203
Mineral, fossil and ren resource depletion	kg Sb eq.	0,629	0,603	0,603	0,821	0,005	0,002	0,027	0,197	0,197	0,197
Ozone depleation	kg CFC-11 eq	0,004	0,004	0,004	0,004	0,019	0,003	0,003	0,003	0,003	0,003
Particulate matter	kg PM2.5 eq	11	12	11	30	46	24	33	90	58	90
Photochemical ozone formation	kg NMVOC eq	471	477	497	1338	1549	2175	4448	5848	1380	5848
Terrestial eutrophication	molc N eq	1672	1707	1673	5015	6103	5017	12821	24116	5137	24116
Water resource depletion	m3 water eq.	277397	265979	269578	363833	-75	114626	100675	1770	1770	1770

). This is not surprising; however the degree is in some categories comparative to the results for the HyMethShip scenarios. When comparing to "ICE – MGO" without metal emissions the impact from the "ICE – MGO" scenario on "Freshwater ecotoxicity", "Human toxicity – non-cancer effects", and "Human toxicity – cancer effects" increases 15.5, 3.5, and 1.13 times respectively. For freshwater ecotoxicity this results in a similar impact as for the HyMethShip scenario, which has 14.9 times the impact of "ICE – MGO". Data on potential emissions of metal during MGO and methanol production is lacking, and toxicity impacts form these emissions sources can therefore not be assessed. This shows that inclusion of more know toxic emissions are required to compare the toxicity of different maritime fuels and propulsion systems.

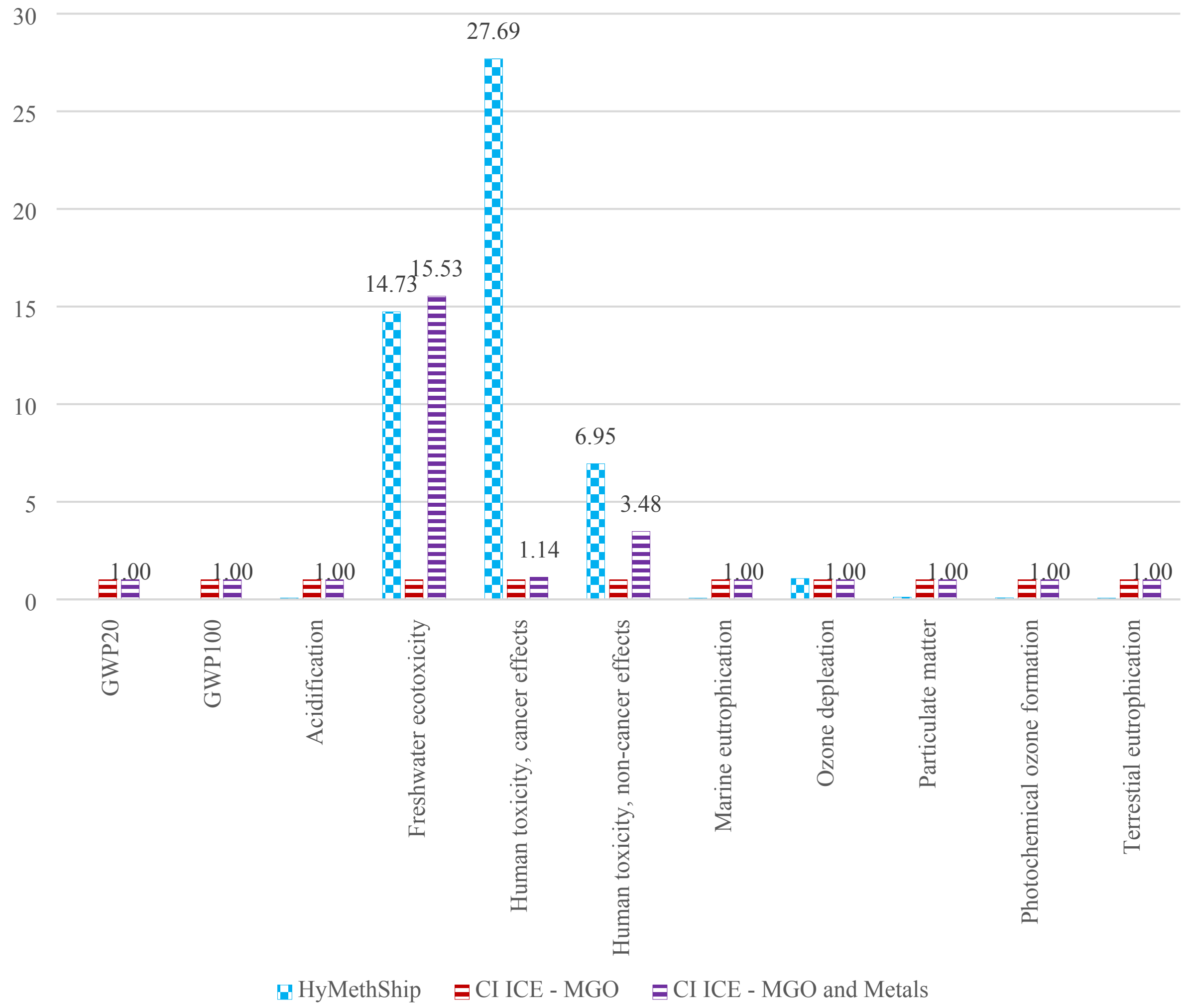


Fig. S10 Relative impact between Marine Gas Oil propulsion when metal emissions from fuel combustion is not included (red) and included (purple). Metal emission estimations from Agrawal et al [27]

13. Results from all life cycle assessment scenarios without normalization

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Ionizing radiation	kBq U235 eq.	0,048	0,053	0,047	0,048	0,227	0,038	0,039	0,044	0,044	0,044
Ionizing radiation E (interim)	CTUe	5692	6225	5625	6036	23022	3886	3932	4240	4240	4240
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