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The HyMethShip Concept: An investigation of system design choices and vessel operation characteristics influence on life cycle performance

Elin Malmgren[a]*, Selma Brynolf[a], Martin Borgh[b], Joanne Ellis[b], Maria Grahn[a], Nicole Wermuth[c]

[a] *Department of Mechanics and Maritime Sciences, Maritime Environmental Sciences, Chalmers University of Technology, Campus Lindholmen, SE-412 96 Göteborg, Sweden*
[b]*SSPA Sweden AB, Chalmers Tvärgata 10, SE-400 22 Göteborg, Sweden*
[c]*LEC GmbH, Inffeldgasse 21, 8010 Graz, Austria*

Abstract

One potential method to decarbonize the maritime transport sector is by using onboard carbon capture technologies. One such potential future propulsion system is the "HyMethShip - Hydrogen-Methanol Ship propulsion system using onboard pre-combustion carbon capture" concept. In this study we use life cycle assessment to analyse the impact of system design choices on the overall environmental performance of the system. Using the HyMethShip on a vessel is shown to lower climate impact compared to today's conventional propulsion technologies. The runtime of the carbon capture system and hydrogen leakage are indicated as the main influencers to the environmental performance besides overall system efficiency. The cost of the HyMethShip system is higher than today's liquid fossil fuel options, but lower than when electro-methanol is used in a conventional engine without applying the HyMethShip concept.

Keywords: alternative fuels; carbon utilization; hydrogen; methanol; emission reduction; shipping

* Corresponding author. Tel.: +46(0)31 772 6548;
E-mail address: elin.malmgren@chalmers.se

1.1.1. Nomenclature

CO_2	carbon dioxide
DAC	direct air capture
dwt	deadweight tonnage
gt	gross tonnage
GWP20	global warming potential over 20 years
GWP100	global warming potential over 100 years
HFO	heavy fuel oil
LCA	life cycle assessment
MCR	maximum continuous rating
MGO	marine gas oil
NO_x	nitrogen oxides
PM	particulate matter
RoPax	roll on roll off passenger
RoRo	roll on roll off
SO_x	sulfur oxides
TEU	twenty-foot equivalent unit
tpd	tonne per day

1. Introduction

Decarbonizing international shipping has been in focus the last decade, still the emissions have increased consistently since 1990 and compared to other transport sectors few regulations or other drivers have been in place (Balcombe et al. 2019). Today's shipping fleet is highly specified and adapted for a variety of tasks resulting in a scenario where decarbonizing the maritime industry will only be feasible if a range of technical solutions are applied. The main propulsion technology used in today's shipping is diesel engines run on heavy fuel oil (HFO). Carbon capture technologies have the potential to contribute to a net-zero emission scenario in several sectors and potentially also in shipping (Daggash et al. 2018; Gibbins and Chalmers 2008; Maher 2018). Ships could use carbon capture technologies onboard and thereby lower emissions from the ship's operations. There are several different carbon capture technologies that can be applied on ships, these can be grouped in three main categories: oxyfuels, pre-combustion capture and post-combustion capture (Koytsoumpa, Bergins, and Kakaras 2018). In this study, we will assess the HyMethShip concept which includes a system for pre-combustion capture of carbon dioxide (CO_2). The HyMethShip concept combines a membrane reactor, a CO_2 capture system, a storage system for CO_2 and methanol, and a hydrogen-fueled combustion engine into one system as shown in figure 1.

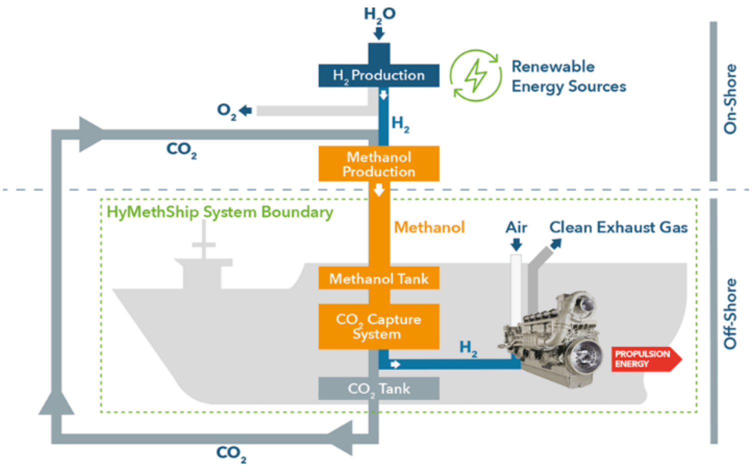


Fig. 1 HyMethShip Concept. Source: https://www.hymethship.com/

The reformer separates the hydrogen from the carbon and oxygen in the methanol, creating a stream of hydrogen leading to the engine. The new concept allows for a closed CO_2 loop ship propulsion system. Compared to other alternative maritime propulsion concepts brought forward in recent years it can be used in combination with a conventional internal combustion engine, limiting the need for new investments, and does not use pure hydrogen as an energy carrier. Methanol can be stored at atmospheric pressure in a similar way as heavy fuel oil and is not associated with the same type of explosion risks as hydrogen.

The methanol in this concept is produced onshore and is of the type "electro-fuels". Electro-fuels are synthetic hydrocarbons, produced from CO_2 and water using electricity as the primary energy source (Brynolf et al. 2018). In this study, the production uses captured CO_2 from the ship and electricity derived from wind power plants, making the fuel renewable and closing the CO_2 loop. Direct use of hydrogen has been shown to have lower life-cycle emissions than electro-fuels in studies focused on light-duty vehicles (Bongartz et al. 2018), but the lower volumetric energy density poses a challenge for the maritime industry, making the HyMethShip system a potentially competitive solution. The goal of this study is to assess the influence of system design choices and vessel operation characteristics on life cycle environmental performance and cost of the HyMethShip system.

This work is part of the European H2020 innovation project HyMethShip (Hydrogen-Methanol Ship Propulsion System Using On-board Pre-Combustion Carbon Capture), which aims to drastically reduce emissions and improve the efficiency of waterborne transport.

2. Method

The HyMethShip system may be used on several different vessel types, but the cost and environmental performance can differ due to the operational profile and ship design. The system assessed in this study is illustrated in figure 2. In the base case for the assessment the CO_2 loss in the system is set to 2%, no hydrogen is lost in the stream towards the engine and methanol combustion is used to start up the reformer during maneuvering from harbor. This is at the current stage of the project deemed as the most probable concept design.

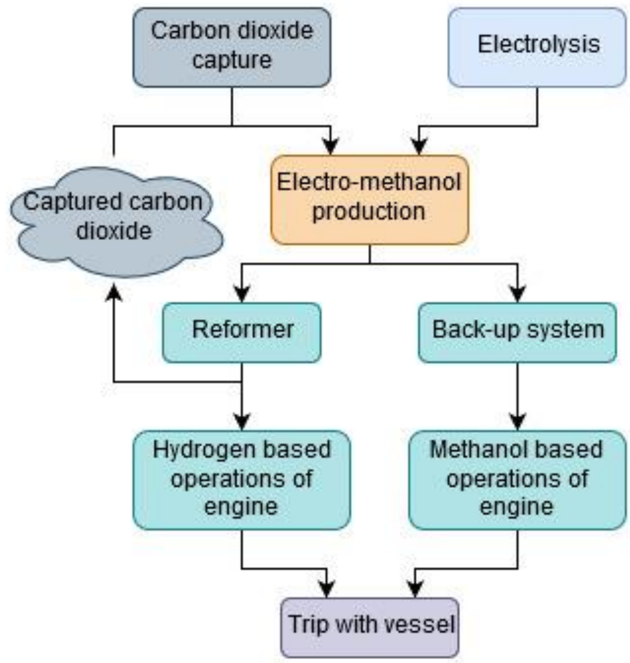


Fig. 2 Simplified schematic over assessed system.

2.1. Assessment of environmental performance

Design choices are explored to establish how different alternative settings in system design parameters influence environmental performance. Three design choices are investigated: (i) engine type, (ii) operation of the membrane reactor, (iii) leakage allowed from unloading of liquid CO_2. Two engine types are considered: a hydrogen/diesel compression ignition engine that uses a diesel pilot injection to initiate hydrogen combustion (lean burn duel fuel engine with diesel as pilot fuel) and a hydrogen/methanol spark ignition engine that can run on pure hydrogen fuel and uses methanol spark ignition for warm-up or emergency operation (spark-ignited engine operation solely on methanol or hydrogen).

This study was performed with a basis in life cycle assessment (LCA). Life Cycle Assessment is a tool used to assess the environmental impact of a product or technology by mapping the emissions from each process in its life cycle (Curran 1993). LCA considers a product's full life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste. LCA has been used to assess the environmental impact from shipping and individual vessels (e.g. Bengtsson, Andersson, and Fridell 2011; Bilgili and Celebi 2013; Brynolf, Fridell, and Andersson 2014; Horvath, Fasihi, and Breyer 2018; Shama 2005) and in these studies, it has been indicated that the use phase of the life cycle has a significant impact on the environment. The use phase can act as a driver for emissions from the resource extraction and production; if more is used more needs to be produced. In this study the environmental performance is investigated by applying life cycle data for the extraction and production of a fuel while varying the functionality of the use phase, and thereby determining the influence of the changed use phase parameters. The emissions included in the foreground system are air emissions as they are the main emissions formed in engine combustion.

Different scenarios are considered for the operation of the membrane reactor, including continuous operation, start and stop, and when the ship is anchored. During start-up of the membrane reactor no carbon can be captured. The potential leakage of H_2 and CO_2 from fuel and storage systems are included and the impact this may have on the environmental performance is assessed. This is done by establishing a worst-case and best-case as suggested by experts within the project. The scenarios have been applied to a 14-hour case voyage with a ro-pax vessel. The trip is characterized by three main phases: maneuvering out from harbor, travelling at speed and maneuvering in to harbor, and the life cycle assessment calculations are based on the energy consumed by the main engine system during these phases. The data has been collected in collaboration with a shipping company.

2.1.1. Data used for life cycle assessment

In this study, only one electro-methanol production route is considered. A summary of the emission data collected can be viewed in table 1. It is assumed that that all heat required is produced using an electric boiler and that no benefits come from heat or oxygen production in the electrolyzer process.

The two engine technologies assessed in the environmental assessment require different fuel types and apply different ignition technologies. The first engine uses a diesel back-up system and the second a methanol back-up alternative, resulting in different combustion emissions. The data on combustion emissions from the methanol back-up indicates pure fuel usage (only hydrogen and only methanol) whereas the diesel back-up engine uses a mixture of the noted fuel and pilot diesel. The hydrogen/diesel combination is a hydrogen/diesel compression ignition engine that uses a diesel pilot injection to initiate hydrogen combustion. This engine combines pilot diesel and methanol at start up, which then is switched to diesel and hydrogen when the reformer is operational. The hydrogen/methanol combination is a hydrogen/methanol spark ignition engine which uses pure methanol combustion at start-up and switches to pure hydrogen combustion when the reformer is operational. Both engines therefore are dual fuel engines optimized to perform well using both fuel set ups. The emission data used for the two main technologies can be seen in table 2.

A comparison to climate change impact for an engine currently in commercial used has been made to indicate the degree of climate impact from the engine systems. The state-of-the-art engine runs on MGO diesel as a pilot fuel combined with methanol from fossil origin and the emissions for this case derives from direct measurements on a running vessel.

Table 1. List of included inflows and outflows for the fuel production.

Process	Reference flow	Outflow	Inflow	References
Hydrogen production	1 kg Hydrogen, compressed to 35 bars	-	11 kg H_2O of drinking quality	van der Giesen, Kleijn, and Kramer (2014)
		-	70 kWh electricity	Bhandari, Chhibber, and Arora (2012)
Carbon dioxide capture	1 kg carbon dioxide	-	3.2 MJ electricity	Fasihi, Efimova, and Breyer (2019)
Wind power production	1 kWh electricity	NEEDS, 1990 kW Offshore wind power plant	NEEDS, 1990 kW Offshore wind power plant	Aggregated LCI data from data base
Electro-methanol production				
Methanol synthesis	1 kg Methanol		1.494 kg CO_2 from carbon dioxide capture	Kiss et al. (2016) Rihko-Struckmann et al. (2010)
And another entry		-	0.197 kg H_2 from hydrogen production	
		-	8.406 MJ electricity from wind power	
		0.118 kg CO_2	-	
		6,9E-7 kg CO	-	
		0.00811 kg H2	-	
		0.00172 kg methanol	-	
		0.58659 kg H2O	-	
Marine Gas Oil				
Aggregated LCI data from data base	1 MJ light fuel oil	ELCD 2011 data set for light fuel oil No. 2	ELCD 2011 data set for light fuel oil No. 2	Aggregated LCI data from data base

Table 2. Emissions from combustion processes. Data source: the manuscript “Emissions to air from a marine engine fueled by methanol” by Fridell and Salo (2019) currently in review proceeding (first section) and project measurements (second section)

Emissions	unit	Hydrogen/ diesel compression ignition engine – 80% MCR	Hydrogen/ diesel compression ignition engine – 20% MCR	Methanol/ diesel compression ignition engine – 20% MCR
Main fuel specific fuel consumption	MJ fuel/kWh	8.56 (Hydrogen)	12.04 (Hydrogen)	12.4 (Methanol)
Fuel oil specific fuel consumption	g/kWh	30	67	67
CO_2	g/kWh	94.5	211.05	1059
CH_4	g/kWh	0	0	-
Emissions	unit	Hydrogen/ methanol spark ignition engine – 80% MCR	Hydrogen/ methanol spark ignition engine – 20% MCR	Methanol back-up spark ignition engine – 20% MCR
Main fuel specific fuel consumption	kWh fuel/kWh	2.47 (Hydrogen)	3.64 (Hydrogen)	2.88 (Methanol)
CO_2	g/kWh	0	0	697
CH_4	g/kWh	0	0	0

2.1.2. Assessment of cost performance

To be able to identify suitable vessel types for the HyMethShip concept, we have assessed the annualized cost of ship operations using the HyMethShip concept and compared it to 3 competing propulsion system concepts (see Table 3). The (i) fuel production cost and (ii)) the cost of the propulsion systems has been assessed. The cost is estimated for the year 2030 and assumes that the technologies are mature. The economic cost difference between a hydrogen/methanol spark ignition engine running on electro-methanol and a hydrogen/diesel compression ignition engine are not quantified within the project (thus far). In this initial cost assessment we do not compare differences in cost due to different developments of the HyMethShip concept but instead we compare with today's conventional technologies using marine gas oil (MGO), natural gas based methanol and electro-methanol. The efficiency of the HyMethShip concept derives from the results of the TRA2020 conference proceeding "The HyMethShip concept: Concept overview, concept development and open issues for concept application in ocean-going vessel" by Wermuth et al. (2020) where the system efficiency potential is stated as 51 %.

Table 3. List of investigated propulsion system concepts.

Propulsion system concept	Fuel production pathway	Propulsion system components considered in the cost assessment	Ship propulsion system efficiency†
HyMethShip	Electro-methanol produced using hydrogen from offshore wind production and CO_2 captured onboard.	Internal combustion engine, reformer, waste heat recovery unit, CO_2 liquefaction unit, liquid fuel storage tank, battery, CO_2 storage tank	51%
ICE MGO	Marine gas oil from crude oil refining	Internal combustion engine, liquid fuel storage tank	45%
ICE NG-MeOH	Methanol from steam reforming of natural gas and methanol synthesis	Internal combustion engine, liquid fuel storage tank	45%
ICE E-MeOH	Electro-methanol produced using hydrogen from offshore wind production and CO_2 from DAC.	Internal combustion engine, cryogenic storage tank	45%

The components of the propulsion system need to be sized for the operational profile and the specific energy requirements of the vessel. The design of the ship energy system is for example not the same for a ro-pax ferry as for a ro-ro cargo vessel. Four different vessels travelling at different speeds with different engine power outputs are compared in this assessment (Table 4).

Table 4. Investigated vessels.

Design parameters	Gross tonnage	Avg. sea speed *(knots)*	Yearly utilization (U)	Avg. installed capacity (kW)	Distance home port and return (hours)
Ro-pax	52000	21.5	50%	20000	28
Cruise ship	70000	21.8	57%	36000	90
Ro-ro cargo vessel (short distance)	33000	20	60%	19200	18
Ro-ro cargo vessel (long distance)	34000	18.5	80%	10800	70

The yearly fuel consumption of the investigated vessels is based on the yearly utilisation, installed capacity (table 4) in combination with an assumed engine load of 80% and the propulsion system efficiency in table 3. The costs for electro-methanol production are based on using best estimates for 2030 (Brynolf et al. 2018). The CO_2 is assumed to be captured by direct air capture (DAC) and a value of 103 Euro/tonne CO_2 (Fasihi, Efimova, and Breyer 2019) is used. The comparative cost for fossil fuels are based on Hansson et al. (2019). For the fossil fuels we have also included an indicative GHG tax of 100 Euro/tonne CO_2 equivalent and the life cycle GHG emissions for these fuels as reported in Brynolf (2014). The HyMethShip system has an advantage in that it does not require

† Defined as the mechanical energy to propeller/chemical energy in fuel based on lower heating value

CO_2 capture for the electro-methanol production as this is captured and supplied by the vessel. The fuel costs are summarised in Table 5.

Table 5. Main costs and assumptions used in the cost assessment.

Item	Formula/Value	Reference
Assumed cost for marine gas oil	9 €/GJ	Assumption
Assumed cost of natural gas-based methanol 2030	9 €/GJ	(Hansson et al. 2019)
Assumed cost of electro-methanol from offshore wind and DAC	34 €/GJ	(Fasihi, Efimova, and Breyer 2019; Brynolf et al. 2018)
Assumed cost for electro-methanol from offshore wind assuming zero cost of CO_2	22 €/GJ	Brynolf et al. 2018b)
Assumed life cycle GHG emissions using marine gas oil (kg CO_2 eq./GJ)	80	(Brynolf 2014)
Assumed life cycle GHG emissions using natural gas-based methanol (kg CO_2 eq./GJ)	89	(Brynolf 2014)
Discount rate	5%	Assumption
Vessel life time	30 years	Assumption
Ship superstructure	1/0.1 ICE MGO propulsion system cost for each vessel	Assumption
ICE MGO	260 €/kW	(Lehtveer, Brynolf, and Grahn 2018)
ICE MeOH	280 €/kW	(Lehtveer, Brynolf, and Grahn 2018)
ICE H2	490 €/kW	(Lehtveer, Brynolf, and Grahn 2018)
Electric motor	270 €/kW	(Baldi, Brynolf, and Maréchal 2019)
Reformer	123 €/kW	(Baldi, Brynolf, and Maréchal 2019)
Reformer membrane life time (operation hours)	60 000	Assumption
Waste heat recovery	103 €/kW	(Livanos, Theotokatos, and Pagonis 2014)
Absorption chiller/ CO_2 liquefaction	500 €/tonne CO_2	Assumption based on data in (Øi et al. 2016)
CO_2 tank	4000 €/tonne CO_2	(Baldi, Brynolf, and Maréchal 2019)
Battery cost (€/kWh)	400€/kWh	(Alnes, Eriksen, and Vartdal 2017)
Methanol tank	24 €/GJ	(Taljegard et al. 2014)
Marine gas oil tank	12 €/GJ	(Taljegard et al. 2014)

The annualised vessel cost is based on the annualised component cost of the propulsion system, the vessel life length of 30 years and a discount rate of 30% (table 5). Based on the operations of the vessels they need different sizes of cryogenic storage tanks. It is assumed that it is only possible to unload CO_2 in the home port as this needs special infrastructure and a buyer for the CO_2.

3. Results and discussion

Results from the comparison of climate change impact from two different HyMethShip set-ups and the current state of the art can be found in figure 3. Both systems have lower emissions of greenhouse gas than today's state of the art methanol/diesel engine systems, as can be seen in figure 3. The state-of-the-art system is run on methanol for fossil sources in combination with MGO as a pilot fuel (similar set up to the hydrogen/diesel engine set-up for the HyMethShip concept). The hydrogen/methanol engine system has lower overall impact than the hydrogen/diesel alternative. This is expected since no fuel is produced directly from fossil sources for the hydrogen/methanol engine system, but fossil diesel (MGO) is used in the hydrogen/diesel system explaining the higher climate impact.

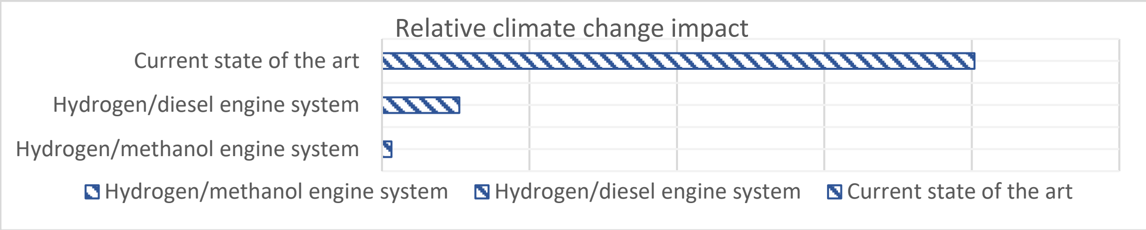


Fig. 3 Comparison of climate change impact

The main influencing emission in the systems is carbon dioxide, which maintains its climate change effect over a long period of time. Therefore no significant difference could be found between GWP100 and GWP20. Had more dinitrogen monoxide or methane been emitted from the system a larger difference would be shown in the results. Although the hydrogen/methanol engine system has the lowest overall impact, there is still potential to reduce this further.

3.1.1. Influential design characteristics

Influential characteristics of the systems are engine type, reformer run time as well as hydrogen and CO_2 leakages from the system. The time the reformer can run during a voyage has a direct influence on how much CO_2 can be captured, and therefore how much CO_2 produced from DAC is needed for the electro-fuel. An illustration of the influence of the reformer runtime can be seen in figure 4, where five different reformer runtime cases are assessed.

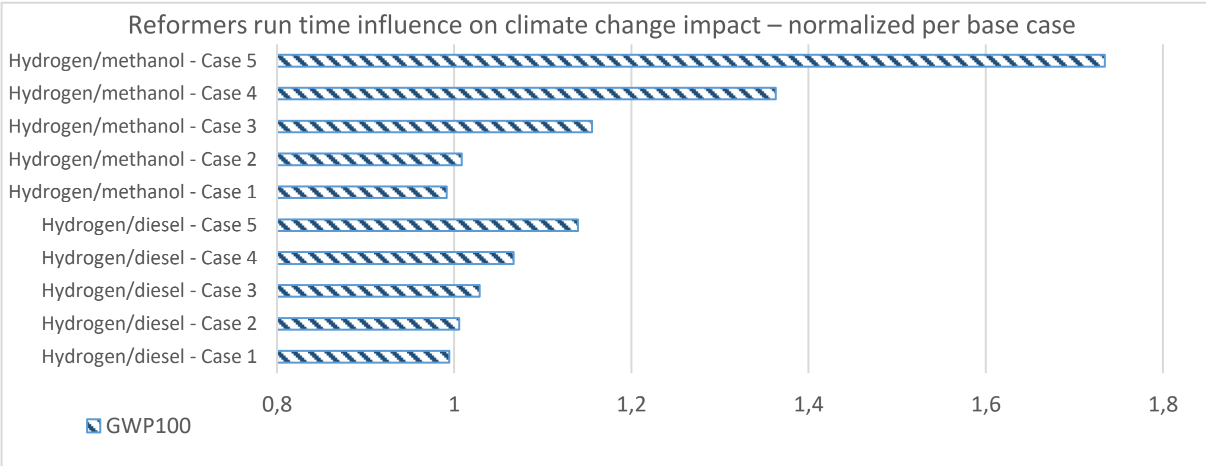
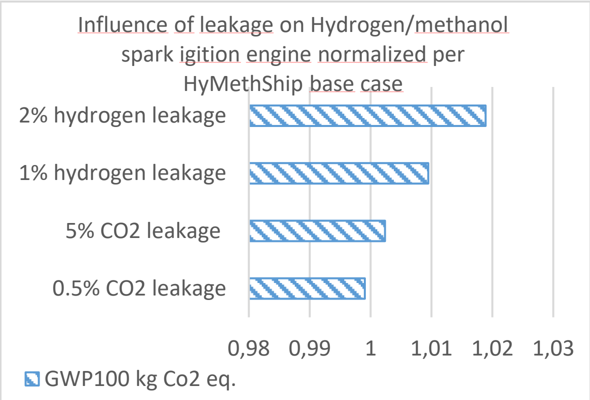


Fig. 4 Reformer runtime case investigation, difference compared to the base case

Case 1 shows a scenario where the reformer is able to run continuously over the entire journey. Case 2 shows a scenario where all maneuvering is performed using the back-up system. Case 3 is a case where an additional 3 hours of the voyage is done with the methanol propulsion instead of the reformer, resulting in larger losses of CO_2 that are not being captured by the reformer. In case 4 half the trip is performed using the methanol set-up and in case 5 the reformer is assumed to not be running at all. Case 5 is presented to give an indication of a worst-case scenario where the reformer has been damaged or is not run due to external reasons. In the base case the vessel maneuvers from harbor using methanol combustion before switching over to the reformer. The CO_2 leakage is 2% and no leakage of hydrogen occurs in the system.

With a longer running time fewer greenhouse gas emissions are mitigated per MJ fuel used. The hydrogen/methanol engine system is influenced by the reformer runtime to a higher degree than the hydrogen/diesel engine system related to the base case. This is mainly because of the overall high impact from the fossil pilot fuel burnt in the diesel alternative. However the difference in absolute impact from running the reformer is larger for the hydrogen/diesel engine system compared to the hydrogen/methanol engine system. The main drivers of climate change impact from the two engine systems using the HyMethShip concept system are the methanol combustion process and emissions from the electricity production processes connected to the fuel production. Lower overall efficiency and lower utilization of the reformer therefore lead to lower environmental performance.

The leakage of hydrogen correlates with the efficiency of the engine, as it is a pure loss from the reformer to the engine. The effect on the results are lower than the percentual loss since the methanol combustion process is not affected by lower reformer performance. For the hydrogen/diesel case the effect is smaller since a larger part of the environmental impact comes from combustion of MGO rather than hydrogen. This indicates that the potential benefit from minimizing hydrogen leakage correlates to how much the reformer is used and that eventual additional costs should be considered in relation to this. Leakage of hydrogen above 2% leads to an increased onboard security hazard and is therefore not assessed. Results from assuming different leakage percentages can be found in figure 5. All investigated scenarios except the 0.5 CO_2 leakage scenario show poorer performance than the base case.



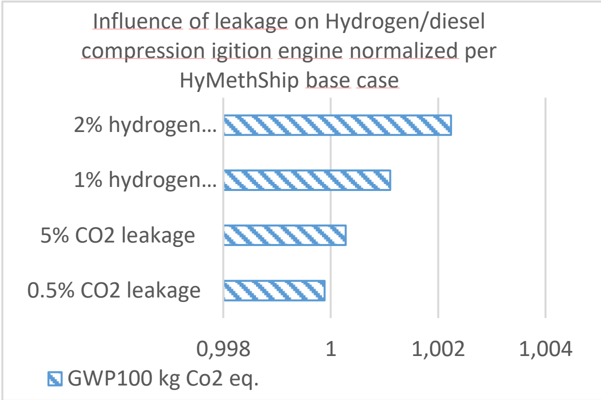


Fig. 5 Climate impact from assuming different leakage percentages. The x-axis shows the ration of GWP between the base case and the investigated scenario. The 0.5% leakage of CO2 scenario is a more optimistic scenario than the base case, where additional care is taken to lower the CO2 emissions from the HyMethShip system.

The amount of allowed leakage of liquid CO_2 mainly depends on the environmental and economic cost of capturing CO_2 from other sources. If this process is expensive the savings from having the circular flow of carbon from the ship to shore will be high. The main impact on the concept when losses of pure CO_2 occurs is that more energy is required in the production of electro-fuel, since less DAC is required to produce electro-methanol for the next voyage. In this assessment emissions connected to the DAC process are low compared to the emissions when hydrogen is produced, resulting in a smaller impact from CO_2 losses compared to hydrogen leakage. This is also true for environmental impacts other than climate change: with more energy required to produce CO_2 the negative contribution to the environment from the HyMethShip concept will increase. From an environmental standpoint minimizing the CO_2 leakage should therefore not be done if this leads to higher hydrogen losses or shorter membrane reactor run time. As carbon capture is still a novel technology securing access to liquid CO_2 might however in itself be beneficial.

3.2. The annual system cost

Results from the comparison of four different fuel and propulsion options for four vessel types can be found in figure 6. The propulsion system cost for the HyMethShip system is high compared to today's liquid fuel propulsion systems for all vessel categories and for all assessed cases the fossil fuel and propulsion system alternatives are shown to have the lowest annual costs, with MGO in an internal combustion engine being the least costly option.

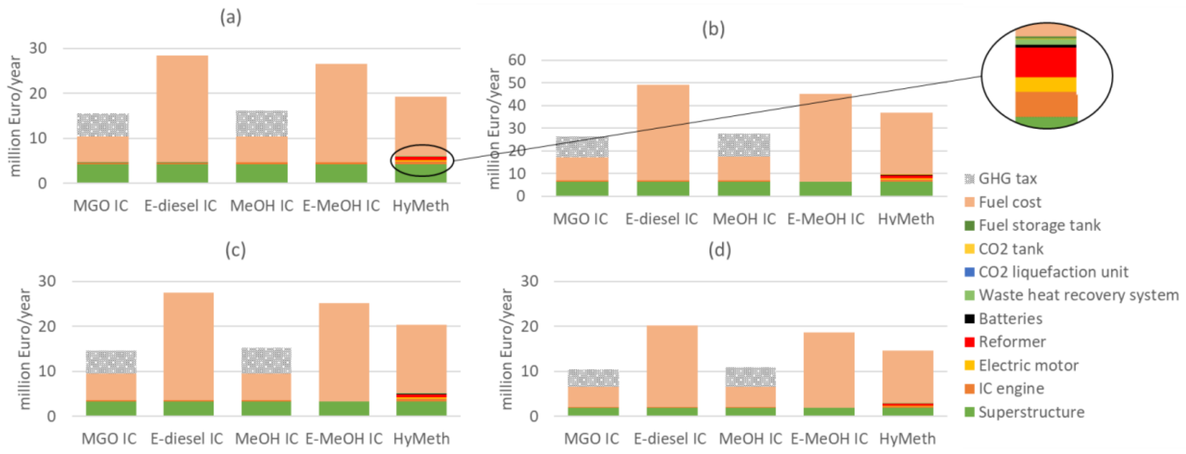


Fig. 6 Annual cost of the propulsion system and fuel for (a) a RoPax vessel (b) a cruise ship, (c) a RoRo ship (9 hours of operations between ports) and (d) a RoRo ship (35 hours of operations between ports) using different propulsion systems and fuels. Note that the scale of Euro per year differs between the charts.

The vessels with HyMethShip show lower costs than for the pure IC engine running on electro-methanol. This indicates that the higher capital cost from using the HyMethShip concept is outweighed by lower fuel cost. The reason for the cost difference is that CO_2 is assumed to have zero cost as it is captured and recycled by the HyMethShip technology. The fuel cost is the largest cost contribution for all assessed propulsion systems and fuels. This is in line with other assessments as earlier assessments have shown that fuel prices for propelling a vessel are currently the largest contributor to a vessel's operational expenses, with estimates reaching as high as 50% of the cost of a voyage factor (Safaei, Ghassemi, and Ghiasi 2019). However, the fuel production cost in 2030 are uncertain and involves cost for novel technologies that have not yet matured.

The costs for reformer electric motor and cryogenic CO_2 tank are the main additional cost items in the HyMeth IC compared to the other options of fuel and propulsion for all vessels. The cost for the fuel storage tank is a small cost item also for the cruise ship scenario where bunkering is only allowed in home port. The carbon tax applied in this assessment does not affect the comparative outcome, as the MGO IC and MeOH IC still perform better. A tax of more than twice the proposed number of 100 Euro/tonne CO_2 equivalent would be needed to shift the relationship between the fuel and propulsion options. In this assessment no cost for DAC was attributed to the HyMeth IC system, where as in reality losses throughout the system will require additional CO_2 from carbon capture. In reality the system wide losses will be between 1-10% depending on production process efficiencies. The capital cost for the HyMeth IC system is highly uncertain as the concept are still under development. These results should just be seen as a first indication of how the system might compare to other propulsion concepts. More accurate and detailed cost assessments will be done later on in the project.

The HyMethShip concept uses methanol, which has a lower energy density than today's fuels (Ellis 2015) . Higher volumes of fuel will therefore be used for the same amount of propulsion power, lowering the travel distance per full fuel tank. This can result in more frequent bunkering, demand for larger tank storage space, and a lower possibility to adapt to current market fuel prices (buying fuel when the price is low instead of when it is needed). Storing the captured CO_2 will also require additional space on board, which also might lower the range a vessel can travel before bunkering. The length of voyages, therefore, becomes relevant for the uptake of HyMethShip. Here two voyage lengths have been assessed using the same type of vessel (but not an identical vessel). As can be seen in figure 6 c-d there is no direct difference in the economic feasibility for the HyMethShip concept for the two voyage lengths assessed here, indicating that length of voyage might not be a cost limitation for the system.

However, the potential cost of lost cargo space is not included in the assessment.

3.3. Applicability of the results

The HyMethShip concept relies on the possibility to debunker CO_2 in port which will be dependent on the available infrastructure in the port. This CO_2 will also need to be transformed into electro-methanol. This puts strong requirements on the available port infrastructure. For vessels based on a flexible route business model, the HyMethShip concept will therefore likely not be attractive until the system is standard equipment. Vessels operating on fixed routes have an advantage compared to others due to the novelty of the system, giving them the potential possibility to secure electro-methanol for bunkering and to off-load CO_2 to reception facilities. The fixed routes are common among ferries and ro-ro cargo vessels as they often travel back and forth between two or three harbours delivering goods and passengers on a somewhat fixed time schedule. Different types of pure cargo carriers can travel on more flexible routes, delivering large amounts of goods when needed to and from various ports.

The vessel could be run on other types of methanol if required by the circumstances. This would no longer be a part of the concept as such but indicates that access to harbor infrastructure and fuel is central to the theoretical concept and not a vessel in a direct emergency scenario. Today’s methanol propelled vessels are mainly using methanol from fossil origins and the main production of methanol is for the chemical industry and not as a fuel. However, if other production routes for methanol are used, such as fossil, the climate impact will be significantly higher, but the vessel as such will be operational.

In the future the system could reach an efficiency of 51% as assessed by Wermuth et al. (2020). The future costs of the system here is based on this assessment. However, the environmental assessment in this study is based on direct measurements on technology still under development. This is done to reflect the current state of development. If the future system efficiency is reached the environmental impact would be lowered than shown in this study.

Within the HyMethShip project an additional version of the hydrogen/diesel engine set-up is discussed where pure diesel propulsion is used for system start-up and maneuvering. Using this set-up instead of the assessed methanol/diesel start-up would result in poorer environmental performance compared to the spark-ignition concept than found here.

4. Conclusions

Initial design choices have an influence on the environmental performance of the system. Losses of CO_2 in the circular flow have less influence than losses of hydrogen as the energy requirements of the hydrogen production process are higher. If a carbon capture technique associated with more or other emissions is used this relation might shift. The climate impact of the HyMethShip system is indicated to be less than for todays conventional methanol combustion engines. The results indicate higher cost of the HyMethShip system than for today’s liquid fossil fuel options, but lower than when electro-methanol is used in a conventional engine without applying the HyMethShip concept.

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