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2025 | 183

A techno-economic evaluation of decarbonization concepts for the shipping sector

Exhaust Gas Aftertreatment Solutions & CCS

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ABSTRACT

Worldwide transport is expected to increase rapidly in the next decades, particularly in the shipping sector. While the International Maritime Organization adopted the 2023 IMO Strategy on Reduction of GHG Emissions from Ships targeting net-zero greenhouse gas (GHG) emissions by 2050, most ships are currently still powered by fossil fuels, thereby emitting greenhouse gases into the atmosphere. Consequently, action needs to be taken as soon as possible. The rapid implementation of innovative technological solutions such as carbon capture or the use of carbon-neutral fuels is therefore critical to achieving the emission targets. Due to the complexity of the diverse ship types in different areas of application and their dependence on available infrastructure and global logistic chains, it is often challenging to identify the optimal decarbonization pathway for specific ship profiles. The use of powerful system simulation tools is ideally suited to support the determination of the best individual solution.

This paper evaluates different approaches towards net-zero GHG emissions for a container ship based on real operating profiles. On the one hand, the application of different technological approaches in the field of carbon capture are compared. In addition to the methods of pre- and post-combustion carbon capture, the capability of oxyfuel combustion is considered. On the other hand, the use of the renewable fuels ammonia and methanol is examined. The study is based on a techno-economic system optimization and evaluation using a highly sophisticated system simulation framework. The analysis of specifically defined key performance indicators (e.g., fuel penalty, CO2 abatement costs) provides a comprehensive overview of the potential of the individual decarbonization concepts for the investigated use case. Furthermore, the fundamental effects that have a decisive influence on the results are discussed and relevant factors for a possible future establishment of the respective concepts are identified.

1 INTRODUCTION

The shipping sector is the backbone of the global transportation network and responsible for ≈ 3 % of global carbon dioxide (CO_2) emissions into the atmosphere [17]. In the next decades, worldwide transport in this sector is expected to increase rapidly [20]. The International Maritime Organization adopted the *2023 IMO Strategy on Reduction of GHG Emissions from Ships* targeting net-zero greenhouse gas (GHG) emissions by 2050, with interim targets of at least 20 % GHG emission reduction by 2030 and 70 % by 2040 [18], yet most ships still run on conventional fuels [6]. The rapid implementation of innovative technological solutions is therefore critical to achieving the emission targets.

In recent years, various concepts for reducing GHG emissions in the shipping industry have been in discussion. Alongside conventional methods, new approaches such as carbon capture (CC) or carbon-neutral fuels have attracted attention. DNV [6] summarized solutions that can contribute to decarbonization in the shipping sector as belonging to one of five categories: logistics and digitalization, hydrodynamics, machinery, energy, and after-treatment. While the GHG reduction potential is limited with some of the approaches, others allow almost complete decarbonization. The following list provides a more detailed overview of various possibilities and their potentials:

- **Logistics and digitalization** efforts can reduce GHG emissions by more than 20 % with speed reduction, optimization of vessel utilization and size as well as alternative shipping routes [6].
- **Optimization of hydrodynamics** has the potential to reduce GHG emissions by 5 to 15 % including measures such as hull coating or air lubrication [6].
- **Optimization of the machinery** includes measures such as efficiency improvements, waste-heat recovery, battery hybridization and fuel cells. These efforts can reduce GHG emissions by up to 20 % [6].
- **Electrification with batteries** is an alternative way to operate ships. If the electrical energy used to load the batteries is produced from green sources, full decarbonization is possible. According to [6], however, battery and hybrid ships currently in operation are of a small size.
- **Carbon capture technologies** can be classified into different categories, cf. [30]: pre-combustion carbon capture (pre-CC), where CO_2 is separated from the fuel before it is burned; post-combustion carbon capture (post-CC), where CO_2 is removed from the flue gas; and oxyfuel combustion (OFC), where combustion occurs with pure oxygen, allowing the CO_2 in the flue gas stream to be separated with low effort. All three options have the potential to reduce the amount of CO_2 emitted to a few percentage points, with each having different advantages and limitations, cf. [14]. Carbon capture has been the subject of research for several decades and is already in use around the world in different sectors [7] including fertilizer production [29], hydrogen production [16], ethanol production [9], methane synthesis [28], and iron and steel production [10]. In the shipping sector, carbon capture has not been established yet, but demonstrators are already in operation, cf. [8] [31].
- **Renewable fuels** include biofuels, methanol (MeOH), ammonia (NH_3), and hydrogen (H_2). These fuels either do not contain any carbon or the carbon comes from non-fossil sources, making them promising alternatives for complete decarbonization [13]. In recent years, attention to them has increased, but they are not yet available in the required quantities [6].

Due to the complexity of the types of ships in different areas of application and their dependence on available infrastructure and global logistic chains, it is often challenging to identify the optimal decarbonization pathway for specific ship use cases. Therefore, this paper is dedicated to the evaluation of on-board decarbonization strategies, with a focus on those strategies that offer a GHG reduction potential close to 100%. In principle, the last three of the options listed above would meet this requirement. However, this study does not consider electrification with batteries due to the high weight and volume of the batteries required for extended trips, cf. [22]; the remaining options are carbon capture and renewable fuels.

A container ship powered by internal combustion engines (ICE) running on fossil fuels was examined as a major CO_2 emitter and representative use case. Following a techno-economic comparison of different retrofit scenarios with carbon capture or renewable fuels, the potential of the individual concepts is discussed. In the area of carbon capture, the following technologies are considered: amine gas treating (AGT) as a post-CC technology, the Hydrogen-Methanol-Ship (HyMethShip) concept [33] as a pre-CC technology and OFC. The area of renewable fuels is represented by green NH_3 and green MeOH. The study is based on a techno-economic system optimization and evaluation using the system simulation framework LEC ENERsim. A comprehensive overview of the potential of the individual concepts is provided by comparing specifically defined key performance indicators (KPI) and finally the fundamental effects that greatly influence the results will be discussed.

2 SYSTEM DESCRIPTION

This section gives an overview of the container ship use case and the related boundary conditions. Furthermore, it briefly introduces the carbon capture technologies under consideration and provides an overview of the current state of the renewable fuels NH_3 and MeOH in the marine sector.

2.1 Container ship use case

The examined container ship has a capacity of approximately 10,000 twenty-foot equivalent unit (TEU) standard containers. The propeller is directly driven by a low-speed two-stroke diesel engine with 34 MW power. In addition, the ship has five high-speed four-stroke auxiliary engines, each with 4.5 MW power, as well as an auxiliary boiler with 3.8 MW power. All engines and the boiler are fueled by very low sulfur fuel oil (VLSFO). The operating profile used in this study assumes a round trip from northern Europe to the western coast of South America, including several intermediate stops, see Figure 1. The whole trip takes 66 days; the longest section without any stops being 10 days. With regard to the required size of the tanks for CO_2 and liquid oxygen (LOX), the ports with appropriate infrastructure to handle these substances are of interest. It was assumed that such infrastructure is available at the port at the beginning and end of the trip as well as at a port roughly halfway along the route. Furthermore, it was assumed that part of the produced engine heat is available for operation of the carbon capture unit, while the rest is used for onboard heating purposes (e.g., fuel).

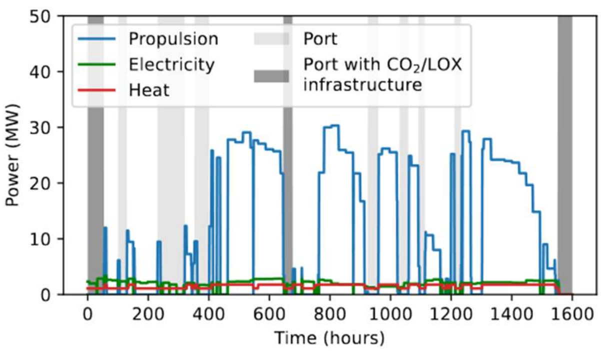

Figure 1: Energy demand profiles of the container ship with port stays with and without CO_2 and LOX infrastructure [39]

2.2 Carbon capture technologies

2.2.1 Amine gas treating

AGT is a post-CC technology in which CO_2 is captured from the flue gas stream, providing the potential to emit an almost CO_2-free gas mixture into the atmosphere, cf. [30]. It is already commercially available for stationary applications, cf. [2] [4] [35].

The technology is based on the chemical absorption of the CO_2 in the flue gas by an amine solution. This study considers monoethanolamine (MEA), which can be regarded as a benchmark. CO_2 is a weak acid, therefore substrates containing basic components such as amine groups are efficient absorbents for CO_2 capture [37]. The process can be characterized as follows [3]: In the absorption column, the CO_2 lean amine solution reacts with the flue gas at comparatively low temperatures of 50 °C or less, enriching the amine by binding it with CO_2. The cleaned exhaust gas exits the absorption column into the environment while the CO_2-rich solution is fed into the desorption column, where it is heated to the desorption temperature of more than 110 °C. The CO_2 lean amine solution is then fed back into the absorption unit and a high purity CO_2 stream is emitted, which can be captured.

It should be noted that the use of MEA can have a negative impact on equipment, as it is a highly corrosive substance [3]. Furthermore, degradation reactions have the potential to form toxic compounds, such as nitrosamines and nitramines [26]. A number of alternatives are currently being researched including secondary amines, which have a higher absorption capacity than MEA [1]. One example is CESAR 1, an aqueous mixture of 2-amino-2-methylpropan-1-ol and piperazine, whose energy consumption is lower and stability is higher than MEA [24].

2.2.2 HyMethShip concept

HyMethShip is a ship energy system concept towards zero-emission shipping using an onboard pre-CC process based on MeOH reforming and separation of the resulting CO_2/H_2 stream. The concept is described in detail in [40] and is briefly summarized as follows.

The system consists of a catalytic membrane reformer that reforms the MeOH feed stream at temperatures between 250 and 350 °C [34] and captures CO_2 in a connected process. While the resulting H_2-rich gas supplies an internal combustion engine, the CO_2 is stored on board for use in onshore MeOH synthesis with H_2 produced from renewable energy sources. The synthesized

MeOH is then used on the ship, forming a closed CO_2 cycle. The thermal energy required for the onboard reformation process is provided by waste heat from the combustion engine supported by a boiler.

2.2.3 Oxyfuel combustion

In an OFC process, cf. [30] [39], a carbon-based fuel is burned with pure oxygen, thereby avoiding the presence of nitrogen in the combustion cycle. As a consequence, the flue gas consists mainly of CO_2 and water (H_2O). Little effort is required to separate out the latter so that a highly pure CO_2 stream remains. Yet to avoid excess oxygen in the exhaust gas, which would be difficult to separate out, the fuel must be burned under stoichiometric conditions. Compared to lean combustion, stoichiometric combustion also has the advantages of needing less pure oxygen and having a lower flue gas mass flow. On the other hand, it has to be considered that this process results in extremely high combustion temperatures, which are critical for the engine components. Application of exhaust gas recirculation (EGR) can lower the temperatures to non-critical levels. A negative side effect of EGR is that it reduces the thermodynamic efficiency of the engine due to changes in the gas mixture as both CO_2 and H_2O replace N_2, resulting in a lower isentropic exponent which reduces the efficiency of the idealized thermodynamic otto cycle.

With regard to the pure oxygen required for the OFC process, it should be noted that the oxygen generated during H_2 production by water electrolysis is often ventilated away, as further handling is currently too costly [11]. Consequently, this excess oxygen could be a cheap and secure source for OFC applications, which could also reduce the price of H_2 production, making alternative fuels more attractive.

2.3 Renewable fuels

This section first summarizes general information regarding the renewable fuels considered in this study. The specific information for MeOH and NH_3 is given in the two subsections.

Basically, the conversion from conventional fuels to renewable fuels in a ship application poses specific challenges. Especially for retrofitting solutions, system integration is an issue. According to [25], important aspects of integration include the increased space requirements for the larger tanks due to the lower energy density of the renewable fuels, safety requirements, the additional costs and larger dimensions of double-wall fuel piping as well as the complexity of the fuel system due to the required safety arrangements (e.g., venting, purging, leak detection).

In the techno-economic system optimization and evaluation, it is not possible to address all of the aspects associated with renewable fuels in detail. For example, the technology readiness level (TRL) of the fuel infrastructure and the combustion concept as well as related components have not been taken into account. It was assumed that the engines have the same efficiency as the conventional engine operated with VLSFO and that onboard fuel handling does not have any limitations. However, the size of the storage tank was adjusted to reflect the different amount of fuel required due to differences in the lower heating value (LHV). Table 1 gives an overview of the fuel characteristics and the storage pressures assumed in this study.

2.3.1 Methanol

Most of the methanol currently produced worldwide is used as an intermediate product for producing other chemicals such as formaldehyde, acetic acid, and plastics. The annual production amounts to ≈ 98 Mt, 99.8 % of which comes from fossil fuels [19]. However, the implementation of methanol as fuel for internal combustion engines on cruise ships and container ships has already begun, as the fuel provides the advantage that it can be easily stored, transported, and distributed as well as blended with conventional fuels [25].

Table 1: Comparison of storage pressures and fuel characteristics

Fuel type	Storage pressure (bar)	LHV (MJ/kg)	Density at storage pressure (kg/m³)	Energy density at storage pressure (GJ/m³)
VLSFO	1	42.8	855.1	36.6
MeOH	1	19.9	794.0	15.8
Liquid NH_3	10	18.6	618.3	11.5

Renewable methanol can be produced from the synthesis of green hydrogen with CO_2 captured from the air or from point sources based on biomass or biogas. The expected production cost strongly depends on the source of CO_2: CO_2 from direct air capture can increase the price range by up to 50 % compared to CO_2 captured from point sources [19]. Bureau Veritas [5] estimates the price of methanol produced from fossil sources to be 70 €/MWh_{fuel}, and the price of renewable methanol to be 225 €/MWh_{fuel} in the near term and 125 €/MWh_{fuel} by 2050.

In conclusion, the limited availability and high production costs of renewable methanol are currently restricting factors for its widespread use in the maritime sector.

2.3.2 Ammonia

Most of the 185 Mt of ammonia produced annually is used as an intermediate product, 80 % of which is for fertilizers and 19 % as a raw material for plastics, explosives and medicine; only 1 % is used directly [21]. In recent years, however, ammonia has been the subject of increased interest as an alternative fuel for large internal combustion engines, cf. [36] [38]. It can be used in spark-ignited combustion engines or in dual fuel compression ignition engines either as pure ammonia or in an ammonia blend. Ammonia blends aim to compensate for the low flame speed and high ignition energy by mixing the NH_3 with H_2 or fossil fuels. This study examines engine operation with pure ammonia.

Green ammonia can be generated from green hydrogen and nitrogen via the Haber-Bosch process. The Haber-Bosch process using non-renewables has an efficiency of ≈ 70 %; however, when the electrolysis of green H_2 is considered, the efficiency drops to ≈ 55 % [21]. Bureau Veritas [5] estimates the price of ammonia generated by fossil fuels to be 135 €/MWh_{fuel}, and the price of e-ammonia to be 190 €/MWh_{fuel} in the near term and 90 €/MWh_{fuel} by 2050. However, these values are subject to a high degree of uncertainty.

Although it has not been taken into account in this study, it should be noted that the TRL of ammonia engines and fuel handling is lower than that of the methanol counterparts [25]. On the other hand, ammonia faces similar limitations to methanol given that the availability of renewable ammonia is also very limited [15]. In addition, ammonia is gaseous under ambient conditions and very hazardous, which makes handling it more difficult. Additional effort is therefore required to store ammonia in its liquid form in order to reduce cargo space losses.

3 METHODOLOGY

The methodology is based on techno-economic system optimization and evaluation using the system simulation and optimization framework LEC ENERsim. A model of each of the defined scenarios was created in LEC ENERsim. Next, the respective ship energy systems were optimized under consideration of the scenario-specific boundary conditions and constraints. By evaluating specifically defined KPI calculated from the resulting simulation data, the various scenarios were assessed and compared with each other. This section explains the core principles behind LEC ENERsim, details the considered ship energy system scenarios, and introduces the defined KPI.

3.1 System simulation

LEC ENERsim is designed to enable techno-economic optimization and assessments of generic energy systems with a generalizable approach, cf. [34]. Based on mixed-integer linear programming, it allows the coupling of different energy system modules via energy flow connections. These modules are grouped into sources, storages, demands, grids, and converters. Using these components, complete energy systems are created by forming mass and energy flow connections between them. The components are parametrized with boundary data, including capital expenditures (CAPEX) and operational expenditures (OPEX), conversion efficiencies, load and source power profiles, lifetimes of the individual components, and energy market data.

For the techno-economic assessment in this study, the net annual costs target function was minimized. The decision variables that were optimized accordingly are the component parameters and the energy and mass flows between the components during each one-hour time step. Details about the target function and decision variables are described in [33] and [34]. In the carbon capture scenarios, the CO_2 capture rate was defined as a constraint.

3.2 Scenario overview

Figure 2 depicts the schematics of the investigated ship energy system scenarios. A dedicated model was created for each scenario. Each model considers a fuel tank, a main engine, five auxiliary engines (only two of which are shown in the schematics), a boiler, and the demand profiles for heat, electricity, and propulsion. The individual schemes and assumptions are explained in more detail further below. The models handle the flue gas stream as a pure CO_2 stream. The component characteristics, however, depend on the respective CO_2 concentrations in the flue gas.

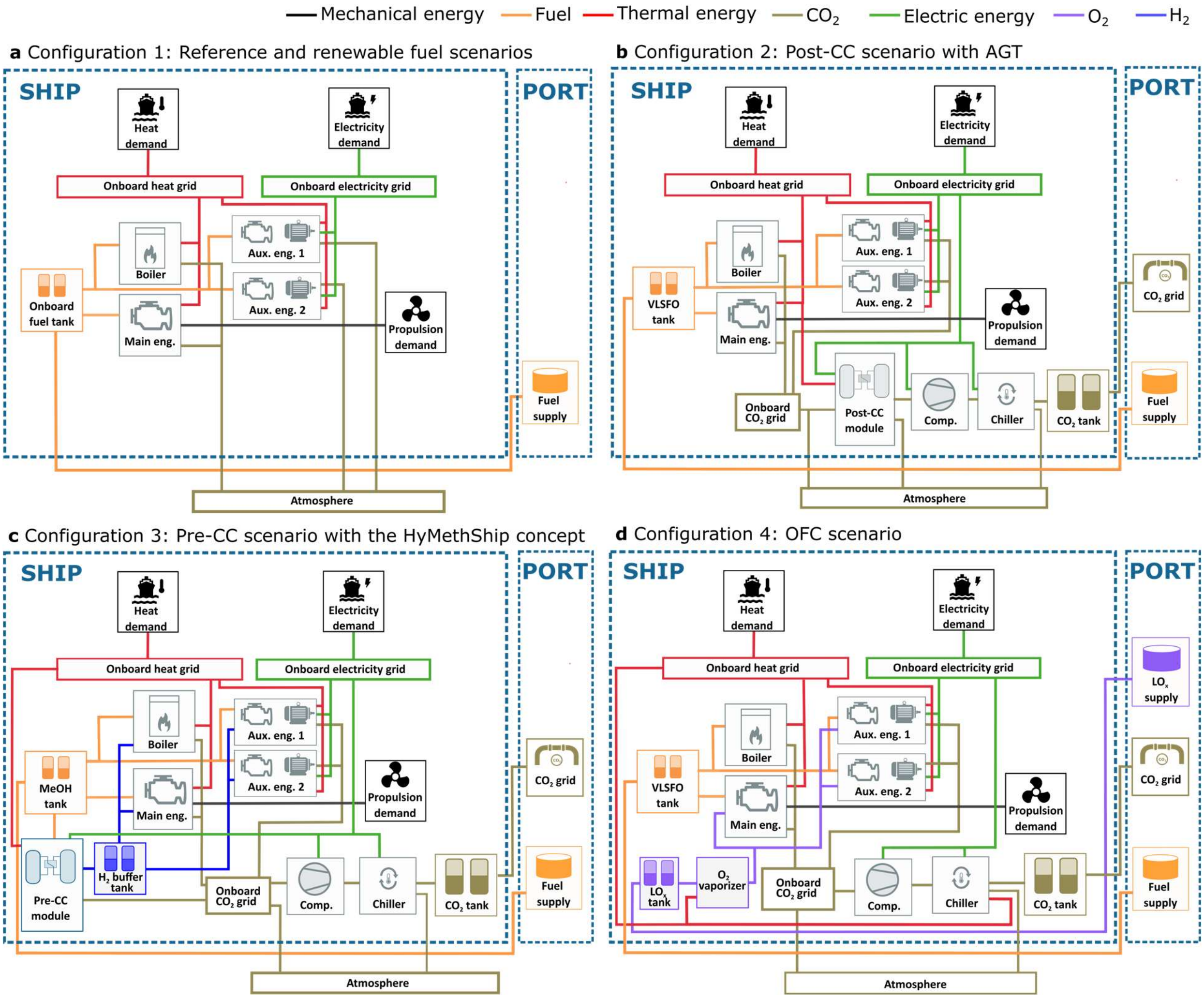

Figure 2: Schematics of the container ship energy system scenarios: (a) Reference without CC and renewable fuel scenarios with MeOH and NH_3, (b) post-CC scenario with AGT, (c) pre-CC scenario with the HyMethShip concept and (d) OFC scenario

Figure 2 (a) represents not only the reference scenario but also the renewable fuel scenarios, which do not require any additional components as compared to the reference scenario. In these scenarios, the parametrization of the fuel tank, engine, auxiliary engine, and boiler was adapted depending on the fuel that was used. It was assumed that the efficiencies of these components are the same regardless of the fuel type.

In the post-CC scenario in Figure 2 (b), the AGT CC unit was added. The capture rate was assumed to be 85 %. The thermal energy for regeneration of the amine solution in the desorption column at 130 °C was assumed to be 3.6 GJ/t_{CO2}, cf. [12] [33]. This energy is taken in part from the waste heat of the internal combustion engines. In addition, 0.05 GJ/t_{CO2} electrical energy was considered for pumps and cooling fans, cf. [27] [33].

In the pre-CC scenario in Figure 2 (c), it was assumed that the engines and the boiler can be operated redundantly, once using H_2 produced by the pre-CC unit and once using MeOH for emergencies. The produced H_2 is stored in a buffer tank to ensure continuous operation. It was assumed that 85 % of the released CO_2 is captured and stored on board for recirculation into the process cycle. The thermal energy requirement for the carbon capture unit is 0.24 GJ/GJ_{MeOH} at 280 °C; the electrical energy requirement is 0.005 GJ/GJ_{MeOH} [33].

Table 2: Economic boundary conditions of the system components

Component	CAPEX	Fixed OPEX [% of CAPEX]	Lifetime [a]	References
Main ICE VLSFO	460 €/kW_{mech}	2	25	[23]
Auxiliary ICE VLSFO	240 €/kW_{mech}	2	25	[23]
Main ICE MeOH	505 €/kW_{mech}	2	25	[23]
Auxiliary ICE MeOH	265 €/kW_{mech}	2	25	[23]
Main ICE NH_3	600 €/kW_{mech}	2	25	[23]
Auxiliary ICE NH_3	370 €/kW_{mech}	2	25	[23]
Boiler	20 €/kW_{chem}	1	30	[39]
Post-CC module	1460 €/kg_{CO2}/h	2	25	
Pre-CC module	520 €/kW_{MeOH}	2.5	9	[33]
CO_2 chiller	200 €/kg_{CO2}/h	2	25	[39]
CO_2 compressor	110 €/kg_{CO2}/h	5	25	
VLSFO tank	0.1 €/kWh_{chem}	2	30	[32]
MeOH tank	0.16 €/kWh_{chem}	2	30	[32]
NH_3 tank	0.16 €/kWh_{chem}	2	25	[32]
LOX tank	6 €/kg	1	25	[39]
CO_2 tank	6 €/kg	1	25	[39]

In the OFC scenario in Figure 2 (d), the engines are operated with pure oxygen, which yields a very high CO_2 concentration in the flue gas. It was assumed that 100 % of the CO_2 from the OFC process is captured. This use case includes a LOX tank with a vaporizer that feeds the main and auxiliary engines with pure oxygen. The oxygen is stored in the tank at 10 bar and -154 °C. Based on an Aspen Plus model (for details see [39]), the vaporization energy demand is 0.1 kWh_{therm}/kg_{O2}. The thermodynamic efficiency of the engine was assumed to be 24 % lower than that of the conventional engines.

In all carbon capture scenarios, the model configurations include the required onboard post-processing. This includes compression, drying and liquefaction of the produced CO_2 as well as onboard storage in liquid form at 15 bar and -30 °C. Based on an Aspen Plus model (for details see [39]), the electricity demand of the compressor is 0.06 kWh_{el}/kg_{CO2} and that of the chiller is 0.05 kWh_{el}/kg_{CO2}.

Table 2 gives an overview of the economic boundary conditions of the individual components of the energy systems. The costs for the post-CC module and the CO_2 compressor are based on cost estimations calculated with the Aspen Process Economic Analyzer; its detailed explanation can be found in [39]. The assumed prices for the fuels and LOX as well as the cost of space on the container ship and costs for CO_2 deposition are shown in Table 3. For VLSFO, average market prices between 2020 and 2022 are considered. For the renewable fuels, projections of the costs in the near term (2030) and the long term (2050) are given.

Table 3: Prices and costs for fuels, LOX, space and CO_2 deposition

Parameter	Value
VLSFO market price [5]	50 €/MWh
E-ammonia price (2030 / 2050) [5]	190 / 90 €/MWh
E-methanol price (2030 / 2050) [5]	225 / 125 €/MWh
LOX price [39]	12 €/t
Cost of space on container ship [23]	1100 €/TEU/trip
CO_2 deposit costs [6]	65 €/t

3.3 Key performance indicators

The system simulation results provide comprehensive component-related data as well as energy and mass flows for each scenario. A number of KPI were calculated from this data for the techno-economic evaluation of the scenarios; the following four are discussed in detail in the next section:

- **Fuel penalty:** Increase in required fuel energy compared to the reference scenario in %. This includes the additional energy required to operate the CC unit and the post-processing devices as well as the additional fuel consumption resulting from the reduced engine efficiency in the OFC scenario.

- **Avoided CO_2:** The difference between CO_2 emitted in the reference scenario and CO_2 emitted in a decarbonization scenario is the absolute amount of CO_2 that is avoided. In this study, the avoided CO_2 is given in % as the ratio between the amount of CO_2 avoided and the amount of CO_2 emitted in the reference scenario. It is not necessarily the same as the CO_2 capture rate because operating the CC unit might incur a fuel penalty.

- **Space demand:** The additional space required to store the fuels, CO_2, and LOX as compared to the reference scenario is given in TEU. The space for additional equipment for the CC units and post-processing devices is not considered.

- **CO_2 abatement costs:** Additional costs that occur in the CC and renewable fuel scenarios compared to the reference scenario per tonne of avoided CO_2 are given in €/t_{CO2}. These are divided into CAPEX for the additionally required components, the additional fuel costs, costs of lost cargo (COLC), CO_2 deposit costs, and costs for LOX. In addition, fixed OPEX is defined as a component-dependent percentage of CAPEX, see Table 2.

4 RESULTS

A major difference between the carbon capture scenarios and the renewable fuel scenarios is the additional fuel required in order to capture and liquefy the CO_2. As shown in Figure 3, this fuel penalty is significant. Among the scenarios, the AGT case incurs the highest fuel penalty of nearly 50 %. This is primarily due to the significant heat demand for solvent regeneration in the desorption column. Since the exhaust gas temperature of the two-stroke engine is comparatively low, the usable waste heat is limited, with most of it previously exploited to heat the fuel oil tanks and pipes. Therefore, additional boiler usage is necessary.

Although hardly any energy is required to remove the CO_2 from the exhaust gas, the OFC scenario also causes a considerable increase in fuel consumption, mainly because of the lower efficiency of the engine with OFC. In the HyMethShip scenario, the additional energy required is mostly for the methanol reformation process. This process is highly efficient for two reasons. First, the energy consumption for CO_2 separation is low, as this process is pressure-driven and takes place directly in the membrane reformer. The pressure increase already happens with low energy consumption in the liquid state before the methanol and water evaporate. Second, part of the thermal energy required for the reforming is recovered, as the chemical energy increases during the reformation of methanol to hydrogen [34] [40]. As the efficiency of both the ammonia engine and the methanol engine was assumed to be the same as that of the diesel engine in the fossil reference case, the renewable fuel scenarios do not show any fuel penalty.

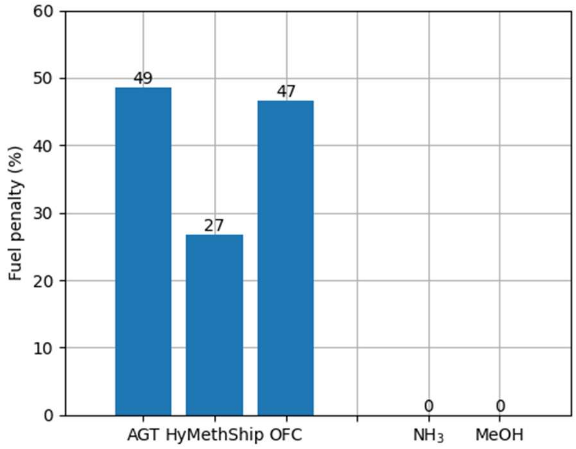

Figure 3: Fuel penalty of the CC and renewable fuel scenarios compared to the reference scenario

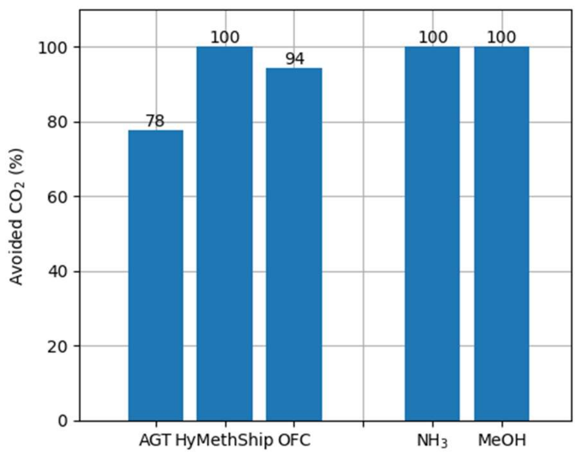

Figure 4: Avoided CO_2 of the CC and renewable fuel scenarios compared to the reference scenario

Since ammonia and methanol are considered to be renewable, 100 % CO_2 can theoretically be avoided as shown in Figure 4. However, it should be noted that life cycle emissions have not been taken into account. In the HyMethShip scenario, 100 % CO_2 can be avoided as well despite the assumed CO_2 capture rate of 85 %. This is because this concept is also based on renewable methanol. The AGT scenario has the lowest CO_2 abatement potential. On the one hand, the capture efficiency is technologically limited and on the other hand, the amount of CO_2 avoided is lower than the amount of CO_2 captured due to the additional fuel required. In principle, the OFC process has the potential to capture almost all CO_2 emissions from the internal combustion engine. In this study, however, it was assumed that the boiler is operated with conventional combustion without CC so that the CO_2 abatement is less than 100 %.

In contrast to onshore applications, maritime settings are highly sensitive to space and weight requirements of decarbonization measures, due to the greatly limited space available on ships. The liquid CO_2 storage unit and renewable fuel tanks are therefore of particular relevance. In general, any space or weight allocated to such systems comes at the expense of cargo capacity.

As shown in Figure 5, the renewable fuels, particularly methanol, require the least amount of space. In contrast, scenarios involving carbon capture demand significantly more space due to the inclusion of the CO_2 tanks. The oxyfuel scenario, which requires 754 TEU (≈ 8 % of the overall cargo capacity), occupies the most space by far since both CO_2 and LOX storage tanks are needed.

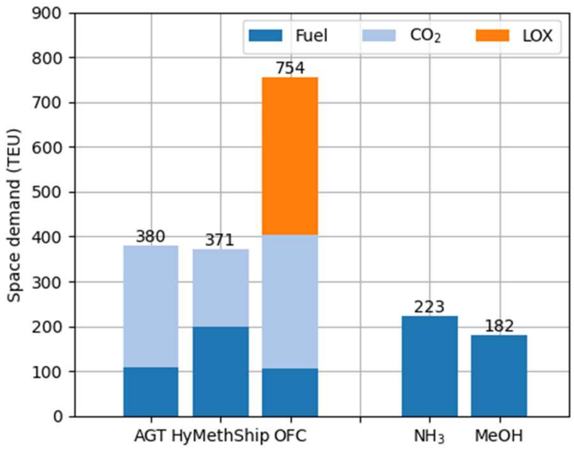

Figure 5: Breakdown of additional space requirements in the CC and renewable fuel scenarios compared to the reference scenario

As seen in Figure 6 and Figure 7, the additional fuel costs are a major contributor to the CO_2 abatement costs in all scenarios. While Figure 6 presents projections for CO_2 abatement costs in the near term (2030), Figure 7 illustrates the long-term costs (2050), which differ solely due to assumptions about the future costs of the renewable fuels. Assumptions regarding investment costs and the costs of fossil fuels remain unchanged. Note that these forecasts are subject to significant uncertainties and should primarily be regarded as qualitative.

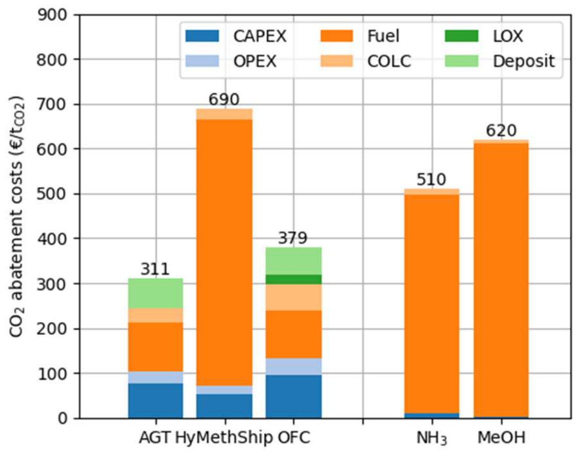

Figure 6: Breakdown of CO_2 abatement costs with short-term (2030) cost assumptions for the renewable fuels

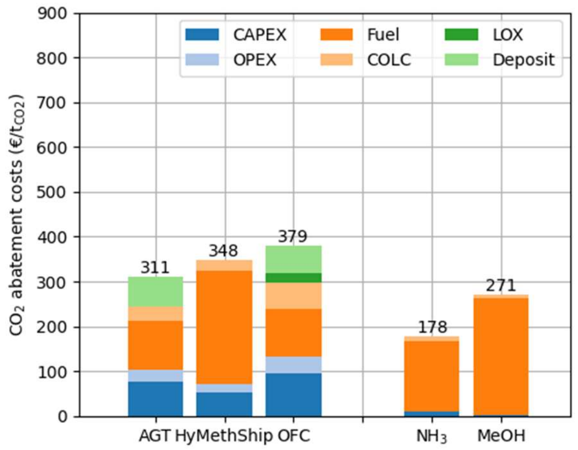

Figure 7: Breakdown of CO_2 abatement costs with long-term (2050) cost assumptions for the renewable fuels

In the ammonia and methanol scenarios, fuel costs absolutely dominate the CO_2 abatement costs as the additional investment costs for the engines and fuel tanks only play a minor role. The space requirement and the associated COLC are also significantly lower in these scenarios than in the carbon capture scenarios, in which the CO_2 storage systems in particular are very space-intensive.

In the AGT and OFC carbon capture scenarios, relatively cheap VLSFO is used. The fuel cost share of the overall CO_2 abatement costs only results from the additional fuel consumption. In contrast, the HyMethShip scenario shows the highest abatement costs in the short-term scenario due to the use of renewable methanol and despite the absence of disposal costs, as the captured CO_2 is not discarded but instead kept within a closed-loop system.

Overall, it can be concluded that onboard carbon capture based on the AGT or OFC processes may represent an attractive short-term solution, with the

AGT process offering significantly lower costs than OFC. The cost disadvantage of OFC is primarily due to the higher investment costs, LOX costs, and space requirements, particularly because additional LOX storage tanks are needed.

In the long term, however, the increased availability and expected lower costs of renewable fuels are likely to significantly enhance their attractiveness. As the cost of renewable methanol decreases, the HyMethShip scenario may also become competitive. The methanol reforming technology would enable a stepwise implementation approach, first working with fossil methanol (not analyzed in this paper) and then switching to a closed carbon cycle with renewable methanol as soon as renewable methanol can be produced cost-effectively in sufficient quantities. Yet in both the short-term and the long-term scenario, it must be taken into account that the HyMethShip concept and the OFC concept have a significantly lower TRL than AGT with MEA as an absorbent.

5 SUMMARY AND OUTLOOK

The transformation of the shipping sector, in which conventional fuels still predominate, to the targeted GHG neutrality by 2050 represents a major challenge. In recent years, various concepts for reducing GHG emissions in this sector have been discussed, such as CC or the use of renewable fuels. Yet due to the complexity of the various ship types in different areas of application and their dependence on available infrastructure and global logistic chains, it is often challenging to identify the optimal decarbonization pathway for specific ship use cases. Therefore, this paper evaluated different approaches towards net-zero GHG emissions by examining a container ship from a techno-economic perspective based on system optimization using the system simulation framework LEC ENERsim. On the one hand, AGT as post-CC technology, the HyMethShip concept as pre-CC technology and OFC were taken into account, and on the other, the use of the renewable fuels MeOH and NH_3.

The results of the techno-economic evaluation reveal that onboard carbon capture based on AGT or OFC may represent an attractive short-term solution, although even in these cases considerable CO_2 abatement costs can be expected in the range of 300 – 400 €/t_{CO2}. However, OFC not only results in higher costs but also has the disadvantage of a lower TRL compared to AGT. The HyMethShip scenario, which is based on renewable methanol, as well as the other renewable fuel scenarios are economically not competitive in the short-term perspective due to the high expected costs for MeOH and NH_3, which make up by far the largest share of the overall CO_2 abatement costs. In the long term, the situation changes so that the lowest costs are expected with the alternative fuel scenarios; the NH_3 scenario is the most attractive with costs of less than 200 €/t_{CO2}.

When interpreting the results, it should be noted that the assumed future price and cost scenarios for system optimization are certainly subject to considerable uncertainty, particularly in the case of renewable fuels. Significantly different price developments in the future can therefore not only lead to significantly different CO_2 abatement costs, but also have an influence on which technology is the most attractive from a cost perspective. Future technical development of the individual technologies will be of particular importance as well. It is not yet clear whether all technologies currently at a comparatively low TRL will become established on the market. Even though they are based on well-researched figures, the results of this study should therefore primarily be regarded as qualitative. However, knowledge of the factors that influence the individual decarbonization concepts can provide the foundation for determining the optimal technology path depending on the respective ship application in the future.

6 ACRONYMS AND ABBREVIATIONS

AGT	Amine Gas Treating
CAPEX	Capital Expenditures
CC	Carbon Capture
CO_2	Carbon Dioxide
COLC	Cost of Lost Cargo
EGR	Exhaust Gas Recirculation
GHG	Greenhouse Gas
H_2	Hydrogen
H_2O	Water
ICE	Internal Combustion Engine
KPI	Key Performance Indicator
LHV	Lower Heating Value
LOX	Liquid Oxygen
MEA	Monoethanolamine
MeOH	Methanol
NH_3	Ammonia
OFC	Oxyfuel Combustion
OPEX	Operational Expenditures
Pre-CC	Pre-combustion Carbon Capture
Post-CC	Post-combustion Carbon Capture
TEU	Twenty-foot Equivalent Unit
TRL	Technology Readiness Level
VLSFO	Very Low Sulfur Fuel Oil

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