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Process and economic evaluation of an on-board capture system for LNG-fuelled CO_2 carriers

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Keywords

On-board carbon capture, maritime carbon capture, zero-emission ships, post-combustion capture, marine engine propulsion

Abstract

Marine pollution is a major concern but one that has to date been largely overlooked; thus, for example, it was not accounted for in the Paris agreement on climate change. Maritime fuel combustion currently contributes 3% of the annual global greenhouse gas emissions. Nearly all shipping-related emissions occur within 400 km of land, and cause death and morbidity to millions of people. The initial greenhouse gas strategy on the reduction of carbon emissions to at least half of its 2008 levels by 2050, adopted by the International Maritime Organization, has the potential to spur innovations and alternative fuel, enabling the shipping industry to adapt to future challenges. Some zero-emission options such as the use of hydrogen and bio-fuels are considered potential strategies, but they lack the infrastructure capacity needed to meet the world's shipping demand. Liquefied natural gas (LNG) has gained substantial interest

as a marine fuel because it can comply with the strictest environmental regulations currently in force, and it is often regarded as a future fuel as most newly constructed ships are built to run on it. Although the use of LNG leads to lower CO_2 emissions compared to traditional heavy fuel oils (HFOs), there is still a need to consider further reduction. A solution which can be implemented is the use of an on-board capture system on ships, also known as ship-based carbon capture.

In this study, a process and economic evaluation was carried out on a solvent-based post-combustion capture process for the energy system of a CO_2 carrier. A rate-based model was developed, validated and scaled up to process the flue gas from a Wartsila 9L46 DF marine diesel engine. Different modes of operation with respect to engine load and capture rate were analysed in this study and the capture cost was estimated. The cost of CO_2 capture was used as an economic index for this study. It was observed via a sensitivity analysis that at 90% capture rate, the cost of capture was at least \$117/t. The effect of exhaust gas recycle was also explored and this resulted in a considerable reduction in the capture cost. The exhaust gas waste heat was utilised and was adequate to supply the required energy needed by the reboiler at each capture rate examined. Also, for LNG-fuelled CO_2 ships, the cold energy obtained while converting the LNG to gas was utilised to liquefy the captured CO_2 from the flue gas.

Nomenclature	
BOG	Boil-off Gas
CAPEX	Capital Expenditure
CCC	Cost of Carbon Capture
CCS	Carbon Capture and Storage
CRF	Capital Recovery Factor
DCC	Direct Contact Cooler
EGR	Exhaust Gas Recirculation
FCI	Fixed Capital Investment
FOPEX	Fixed Operating Expenditure
GHG	Greenhouse Gas
IMO	International Maritime Organisation
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MEA	Monoethanolamine
PM	Particulate Matter
TAC	Total Annual Cost
TDPC	Total Direct Plant Cost
TEC	Total Equipment Cost
TIPC	Total Indirect Plant Cost
VOPEX	Variable Operating Expenditure
WHRS	Waste Heat Recovery System

1. INTRODUCTION

Carbon dioxide emissions from shipping activities contribute approximately 3% (1.1 Gt) of global greenhouse gas (GHG) emissions per year [1] and this represents a growing concern, as it was not included in the Paris Agreement on Climate Change. The International Maritime Organisation (IMO) introduced two measures to address GHG emissions in 2008, the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP). The latter is directed to all ships, and the former is a set of design standards for new ships manufactured after 01 January 2013.[2] Despite the adoption of these measures, at the EU level, CO_2 emissions are expected to rise above 1990 levels by 86% in 2050 if nothing else is done.[3] Consequently, the European Union Monitoring, Verification, and Reporting (EU MVR) regulation was adopted in 2015 to report annual fuel oil consumption and CO_2 emissions for all ships from and around the EU area.[3,4] This is expected to cut down the level of CO_2 emissions from each journey by 2%.[5] Additionally, in 2016, the IMO CO_2 Data Collection System (IMO DCS) was also adopted to cover shipping emissions globally, and the fuel consumption data collection has started in 2019. The EU MVR and IMO DCS represent steps to reduce GHG emissions from ships. The IMO decided to place a cap on global GHG emissions, limiting them to at most 50% of 2008 levels by 2050.[6] The capacity at which major banks (Citi, Societé Generale, Danish Ship Finance, Danske Bank, etc.) lend to shipping companies is also now influenced by their technology cleanliness and environmental consequences with reference to climate change.[7]

The initial IMO GHG strategy and the banks' new policy can be seen as giant steps for the shipping industry in terms of cutting down carbon emissions, bringing them closer in line with the Paris Agreement and capable of spurring new and innovative methods for emission reduction.[6] Various efforts are already in force on the reduction of carbon emissions, such as:

speed reduction, energy efficiency, low-carbon fuels use, and renewable energy sources,[5,8–13] but limited work has been carried out on on-board carbon capture. On-board capture systems can be seen as a transition plan to lower carbon emissions in the maritime industry, giving sufficient time for zero-emission technologies to be fully developed.[4] Although there are different available methods (pre-, oxy- and post-combustion capture processes) for capture, a viable process is dependent on limited parasitic load permissible for the ship's energy system and its space capacity.[14,15] The post-combustion process requires limited transformation of the internal combustion engine, compared to pre- and oxy-combustion, favouring the constraint of space.[15] Process System Enterprise (PSE) and Det Norske Veritas (DNV) concluded a concept design for on-board capture using a post-combustion process, the results estimating that the process is feasible and capable of reducing maritime CO_2 emissions by 65%.[16] A solidification method was developed for CO_2 storage on-board for separating CO_2 emissions from the exhaust gas. The CO_2 emitted after reaction exists as precipitated calcium carbonate, and can be stored safely on-board or unloaded at any appropriate destination.[14] Luo and Wang[17] recently developed a solvent-based capture process to capture CO_2 from the energy system in a typical cargo ship. The capture rate of 73% was achieved without additional supply of heat or electricity. A study was carried out on a Liquefied Natural Gas- (LNG)-fuelled vessel; CO_2 was captured from the exhaust gases on-board, and the reference vessel was re-designed to accommodate the capture equipment.[18] The combined capture of CO_2 and SO_2 was evaluated for on-board use, utilising aqueous ammonia to avoid space constraints and meeting current and future regulations.[19] Feenstra et al.[4] evaluated the feasibility of adapting CO_2 capture for natural gas- and diesel-fuelled carriers using different solvents (monoethanolamine (MEA) and aqueous piperazine) at different desorption pressures.

Carbon Capture and Storage (CCS), amongst others, was listed among the technologies needed to limit the global temperature rise to below 2 ^{0}C. [20] Most of these consist of capture from large point sources to a secure storage location. The storage of CO_2 from single or multiple point sources is incomplete without an efficient transportation system. This can be accomplished by the use of trucks, train, pipelines or ships. However, ship-based transport can be a better option because it offers more flexibility with regard to location of source and sink, and can deal with smaller CO_2 quantities, longer distances and shorter project durations.[21,22] Elementenergy[22] compared the cost of transporting 1Mt CO_2/a by ship and pipeline over a distance of 600 km for 20 years, and found that cost reductions for ship transport are less dominated by necessary capital expenditure.

The gas carriers available for ship transport of CO_2 are generally of small capacities (800 - 1200 m^3) as compared to that needed for other commodities.[21] Semi-pressurised vessels are viable for large-scale transport of CO_2 at conditions near the triple point.[21,23,24] A combined Liquefied Petroleum Gas (LPG)/CO_2 semi-refrigerated ship was chosen for a complete transport chain analysis of CO_2 between capture and storage, with a storage capacity of 20,000 m^3 at -52 °C and 6.5 bar.[21] A LPG carrier retrofitted for CO_2 use was also considered for on-board capture of CO_2 and SO_2 emissions at conditions close to the triple point.[19] The cost effectiveness of large-scale ship transport has been examined in the literature [23,25–28] and it is generally concluded that this can be a cost-effective option.

Some zero-emission options include the use of hydrogen and biofuels as alternatives to fuels of diesel quality (HFOs, low-sulphur heavy fuel oil), but such fuels lack the infrastructure capacity needed to meet the world's shipping demand, although biofuels have been identified as having lower life-cycle CO_2 emissions compared to conventional HFOs.[8,29] By contrast, LNG has garnered substantial interest as a marine fuel because it can comply with the strictest environmental regulations currently in force. It is often regarded as a future fuel as most newly constructed ships are built to run on it. LNG consists mainly of methane, with a negligible sulphur content and higher hydrogen-to-carbon ratio compared to the traditional HFOs, resulting in 20-30% lower CO_2 emissions on combustion.[30] Although these carbon reductions are beneficial, they offer no guarantee against future stricter regulations. Therefore, a solution that can be adapted to offer deep emissions reductions is needed—ship-based carbon capture and storage.

This work evaluates the process performance of a capture system on LNG-fuelled CO_2 ships at different engine loads. The capture system was designed using aqueous ammonia solution, varying concentration to ascertain its effect on the reboiler duty, hence, the thermal energy demand. The choice of an NH_3-based process over MEA is made here primarily because of the total energy requirement for such a process. Thus, it was estimated that the NH_3-based process needed only 27% of the energy requirement of the MEA-based process.[31–34] In addition, using aqueous ammonia offers some benefits in comparison to MEA: no corrosion problems, higher loading capacity, multi-pollutant capture and production of value-added products such as ammonium sulphate, ammonium nitrate, and ammonium bicarbonate.[34] However, the drawbacks of using NH_3 in place of MEA can be seen in terms of its slow kinetics for absorption, and volatility requiring larger-capacity equipment and abatement systems.[32,35,36] However, exhaust gas recirculation (EGR) can increase the concentration of CO_2 and the overall performance of the capture system. In this study, the exhaust gas serves as a heat source available to provide energy for the reboiler duty. The capture system is operated at a high pressure, decreasing the energy required for compression and liquefaction of the captured CO_2. The cold energy from the LNG can also act as a heat sink to provide cooling capacity for the captured CO_2.[4]

Cost evaluations were carried out for the reference ship type, LPG/CO_2 retrofit. The calculated cost of captured CO_2 was compared and observed to be dependent on the engine size, the capture rate adopted and the choice of technology. Different modes of operation were considered at a percentage of full engine power: sailing, manoeuvring and hoteling at 85%, 75% and 50%, respectively. However, the mode of operation feasible for normal operation of the capture system is 85% load, whilst sailing. In future, an added IMO GHG strategy could include a carbon tax for CO_2 shipping emissions [4]; this was also evaluated as a possible scenario to encourage ship owners to adopt new technology such as ship-based carbon capture.

2. METHODOLOGY

The integrated ship model consists of the ship energy system and the capture plant installed on-board as shown in Figure 1. The model involves the flue gas stream going into the waste heat recovery system (WHRS); the retrieved heat is used to supply thermal energy for heating, if needed, then the flue gas goes into the post-combustion capture process. All NO_X and particulate matter (PM) are assumed to be removed upstream of the absorber. Considering the type of fuel used (natural gas - composition as shown Table S1), there are no SO_X emissions. The flue gas contacts the solvent counter-currently in the absorber, the CO_2-depleted stream is released to the top of the absorber, and then the CO_2-rich stream is pumped to the stripper column for regeneration. To store CO_2 on-board a ship, it must be stored as a liquid to minimise space used for storage tanks. The LNG vaporisation unit on-board LNG-fuelled vessels can serve as a heat sink for the liquefaction of CO_2, thus avoiding the need for a refrigeration unit.[4]

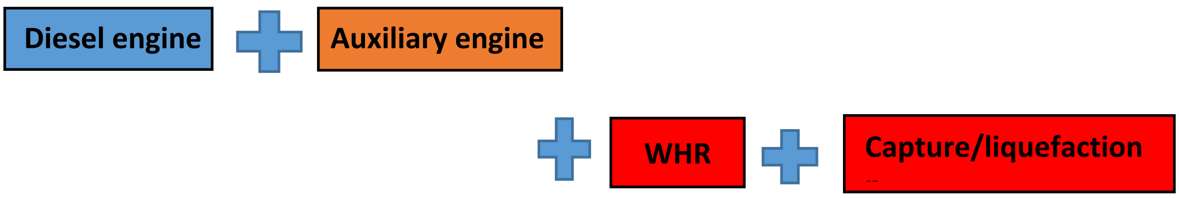

Figure 1: Schematic of the integrated ship model

2.1 Ship energy system

The ship energy system provides the necessary power required for propulsion and electricity generation on the ship. It consists of a propulsion system, auxiliary generators and a WHRS for energy efficiency. The main engine, which is the primary source for propulsion and auxiliary power generation on-board, is modelled by Luo and Wang[17] . The engine selected for all cases was the Wartsila 9L46DF, a 4-stroke dual-fuel engine that can run on either natural gas, HFO or marine gas oil. For validation purposes, the model was compared to the Wartsila 9L46DF engine handbook performance data[37] and the results obtained appear to be in good agreement as shown in Table 1. The reference case is a LPG vessel that can be retrofitted for CO_2 use at different loads.[19] The additional power requirement for capture, storage and liquefaction of the captured carbon emissions was assumed to be 1 MWe and the new reference exhaust gas data at varying loads are shown in Table S2. The exit temperature of the exhaust gas from the main engine at respective loads selected was taken to be 362 °C. Thereafter, the gas passes through the WHRS and is then further cooled in a direct-contact cooler (DCC). In the DCC the flue gas is cooled down as a result of direct contact with cooling water. As the cooling process employs water condensation, the flue gas at the exit of the DCC has a reduced water content.[38] In the integrated ship model, it is assumed that all the NO_X and particulate matter are removed upstream of the absorber and the direct contact cooler is further used to reduce the flue gas temperature to 20 °C.

A ship run on natural gas emits only half the CO_2 emissions of one using conventional fuel, HFO. For instance, CO_2 concentration in flue gas from a natural gas combined cycle power plant is about 3.5 - 4.5 mol% while from a coal-fired power plant, it is 11-13 mol%.[39] A low concentration of CO_2 results in low absorption efficiency and exhaust gas recirculation is an effective solution.[40,41] In this study, the flue gas was split into two streams, one linked to the post-combustion capture process, and the other recirculated to be mixed with fresh air. The EGR ratio was varied from 10-30% as calculated by Eq. (**1**), thus the flow rate of fresh air intake is reduced, respectively (Table S3). Consequently, the flowrate of the flue gas going into the capture process decreases, whilst the CO_2 concentration increases as shown in Figure 2.

$$\text{EGR ratio} = \frac{\text{Mass flow of recirculated exhaust gas}}{\text{Mass flow of exhaust gas}} \qquad (\mathbf{1})$$

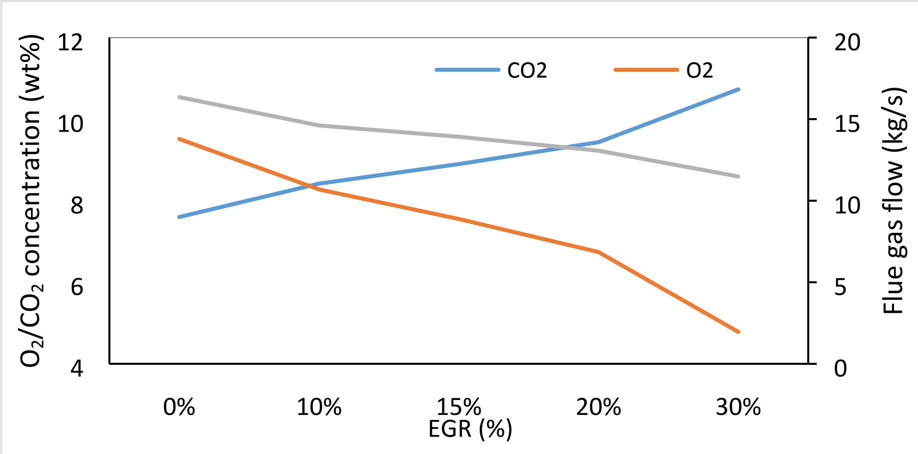

Figure 2: Impact of EGR on O_2 and CO_2 concentration in the exhaust gas at 85% load

2.2 Capture system

In this study, the ammonia capture system was validated with the Munmorah pilot plant data,[42,43] as detailed elsewhere.[19] Figure 3 shows the Aspen® flowsheet of the post-combustion capture. All columns were modelled with the rate-based approach and packed with pall rings. The main parameters characterising the developed full-scale capture process can been seen in the supporting information (Table S4 and Table S5). Since the engine is fuelled by LNG, there is no need for SO_X scrubbers. The exhaust is passed through an integrated heat exchanger for thermal energy generation, and is further cooled down. For the capture process, the flue gas from the ship energy system is fed to a blower into the bottom of the absorption column. The CO_2-depleted flue gas flows out to the atmosphere, after passing through the wash column. The CO_2-rich ammonia solvent flows into the regeneration tower where ammonia is separated from the CO_2 by the heat supplied by the reboiler. The regenerated lean solvent returns to the absorption tower after passing through the heat exchanger and cooler. Washing water is sprayed at the top of the absorption and regeneration columns to recover ammonia, and the wastewater is sent to the treatment plant on-board the ship for ammonia recovery, which is kept in storage tanks and used for the subsequent make-ups required by the capture process. The ammonia loss in the process of recovery from the waste water was assumed to be 10% and this was made up by fresh ammonia solvent.

Table 1: Validation of the Aspen® Plus Diesel Engine Model Performance [37]

Load (%)	Fuel flowrate (kg/s)	Air flowrate (kg/s)		Engine output (kW)	Flue gas flowrate (kg/s)
100	0.450	16.6	Handbook	10305	17
			Model	10292.76	17.05
			Difference	0.0012	-0.003
85	0.384	14.11	Handbook	8759.25	14.45
			Model	8748.57822	14.494
			Difference	0.0012	-0.003
75	0.343	12.45	Handbook	7728.75	12.75
			Model	7718.6	12.793
			Difference	0.0013	-0.003
50	0.241	8.3	Handbook	5152.5	8.5
			Model	5143.55	8.541
			Difference	0.0017	-0.005

The ammonia concentration was varied between 4 and 10 wt% to evaluate the effect on the capture process parameters. The impact of EGR on the energy demand for the absorption process for this case study, applied to the ship model, was investigated at 4 wt% ammonia concentration. Simulations showed that as the concentration of CO_2 increased, the specific reboiler duty decreased (10.5 MJ/kg-CO_2 to 7.5 MJ/kg-CO_2) due to the higher CO_2 partial pressure and, hence, favouring the capture reaction (Figure 4). Therefore, the higher the CO_2 concentration in the flue gas, the more efficient the stripping process becomes. The reduced exhaust gas flow into the absorber due to EGR causes a substantial decrease in capital expenditure of the capture system as compared to that without EGR. Since at approximately

11 wt% CO_2 concentration (30% EGR), the least energy consumed was observed, for further analysis in this work, 30% EGR was used.

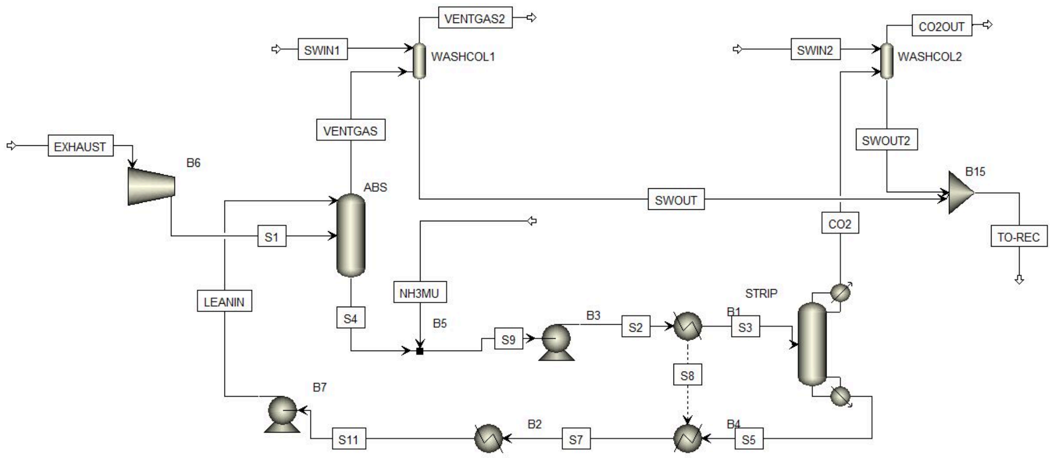

Figure 3: Aspen® (V10) flowsheet of the post-combustion CO_2 capture unit

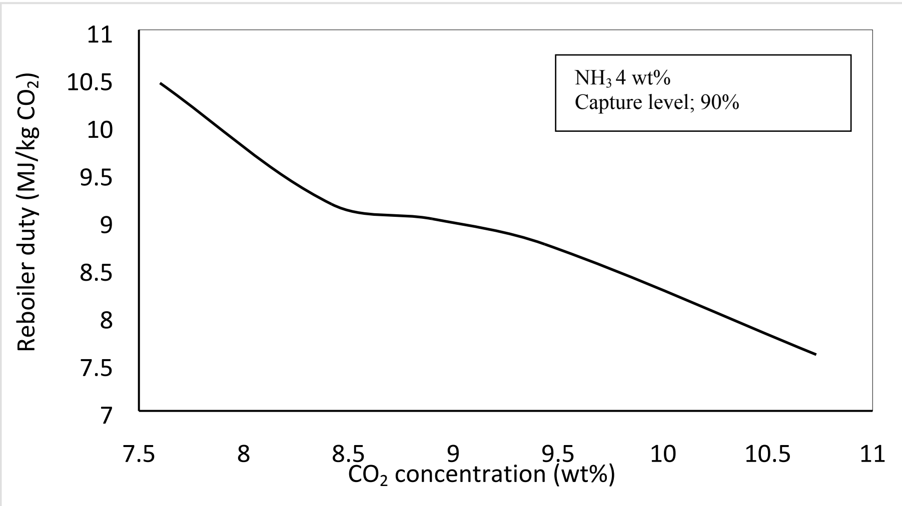

Figure 4: Effect of CO_2 concentration on reboiler duty at different capture level

2.3 Compression and liquefaction system

Considering the limitations of space on-board ships, the captured CO_2 must be conditioned to be stored as a liquid. The volume of liquefied CO_2 is about 1/600 that of gaseous CO_2 and, hence, larger quantities can be stored on board. The condition of -50 °C and 7 bar near the triple point was selected for this work. Re-liquefaction of the boil-off gas (BOG) and the captured CO_2 is considered for liquefaction into the cargo tank. The BOG rate is assumed for this work to be 0.2% per day and is calculated via the method used by Yoo[44] and Awoyomi et al.[19] With the ammonia case adopted, desorption pressure at 6 bar was considered for all cases, and one compressor only is enough to attain the desired pressure of 7 bar. In attaining the required temperature, a cross-heat exchanger was added to provide the cooling duty necessary for liquefying CO_2 as shown in Figure 5. The cooling duty can be attained from the already stored LNG, upon entering the engine for combustion. The simulation results are shown in Table S6. The cold side integration is the exchange of cold energy that could have been left unused when vaporising the liquefied natural gas for engine combustion. The amount of LNG vaporised determines the energy capacity or cold energy available for liquefaction.

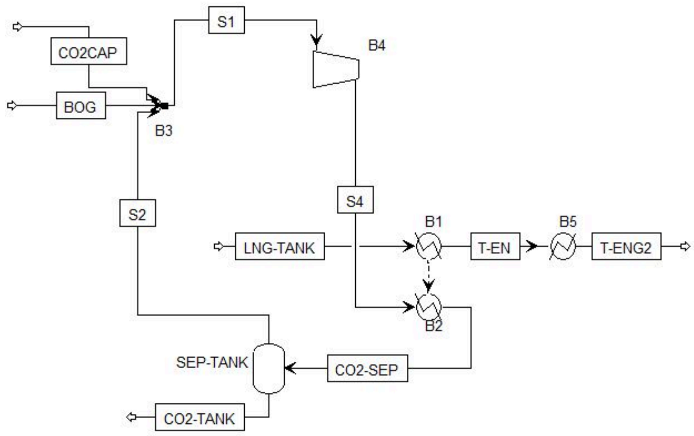

Figure 5: Aspen® flowsheet for compression and liquefaction of the captured CO_2

3. RESULTS AND DISCUSSION

3.1. Thermal performance of the integrated system

Table 2 summarises the thermal performance for the three cases considered in this study. In the reference case, the propulsion as well as the electrical power generated from the main engine is 8.8 MW. Some thermal energy is also generated on-board from the WHR unit if required and it is approximately 3.5 MWth. In both Case 1 and 2, extra power of 1 MWe is supplied to accommodate the power consumed due to the installation of CCS. In Case 1, the carbon capture level can reach 90% with the same thermal energy provided on-board as in the reference case. With the accommodation of EGR, the flue gas flowrate reduces, but the carbon capture level achieved can reach 90%.

Table 2: Thermal performance of the ship energy system with/without the EGR system

Description	**Reference case**	**Case 1: With CCS + no EGR**	**Case 2: With CCS + EGR**
LNG consumption (kg/s)	0.384	0.45	0.45
Propulsion/Electrical power output (MW)	8.8	8.8	8.8
Extra electric power output (MWe)	-	1	1
Auxiliary electric power consumption in capture process (MWe)	-	0.1	0.07
Electric power consumption of CO_2 compression and liquefaction MWe)	-	0.4	0.25
Stripper reboiler duty (MWth)	-	3.4	2.7
WHR thermal energy output (MWth)	3.5	3.5	2.8
Capture level (%)	-	90	90

3.2 Process analysis

1. Effect of NH_3 concentration

The most important parameters affecting the performance of a capture system are the solvent recirculation rate and the reboiler duty. The performance of the model in the form of capture efficiency was determined by varying the solvent circulation rate at different ammonia concentrations whilst keeping the composition of flue gas, lean loading and stripper pressure constant: CO_2 concentration in the flue gas 11 wt%, stripper pressure 7 bar, NH_3 concentration varied from 4 – 10 wt%. The purity of the CO_2 captured was at 99% after exiting the water wash column for ammonia removal and other impurities were in negligible amounts. The results plotted in Figure 6 show the reboiler duty against the capture efficiency at different NH_3 concentrations. The changing energy demand of the reboiler duty is attributed to a number of components, specifically: sensible heat, latent heat, heat of reaction and the heat of dissolution.[36] These represent the summation of the energy required for solvent regeneration in the stripper. The solvent recirculation flow was varied to attain the required capture rate for each concentration as shown in Figure 7. As can be observed from both Figure 6 and Figure 7, at 10 wt% NH_3 concentration the lowest reboiler duty and solvent recirculation flow were obtained compared to the rest. Increasing the solvent concentration reduces the solvent flowrate, thereby reducing the sensible heat required. As the solvent concentration increases, the water fraction reduces, which reduces the heat of vaporisation of water.

Although with the increase of solvent concentration, there is the benefit of minimising the reboiler duty, the quantity of pure ammonia required increases co-currently, hence, leading to an increase in ammonia emissions. As the concentration increased, the amount of NH_3 emitted from the absorber column increased but this was avoided using an NH_3 abatement system, a wash column, to guarantee levels less than 50 ppm. Given the choice of NH_3 concentration, a trade-off would need to be determined based on its effect on the capture process or the added or extra NH_3 abatement system.[45]

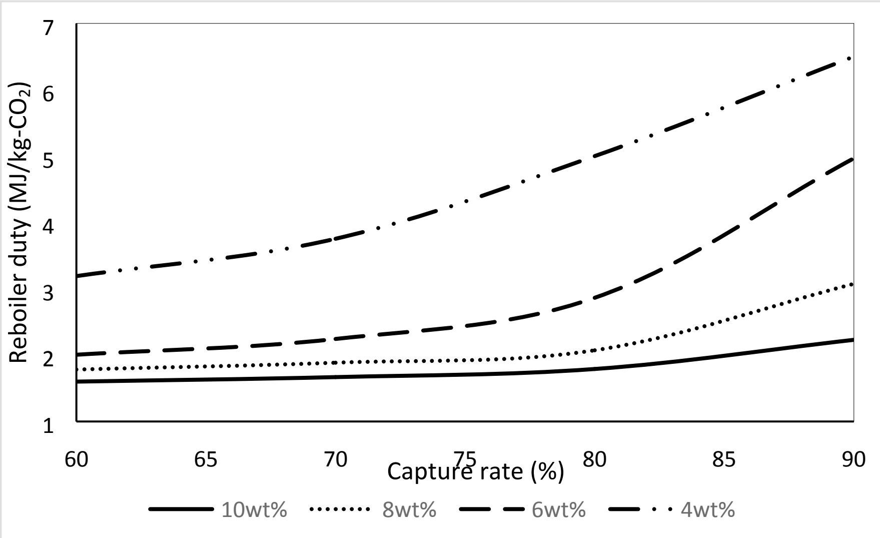

Figure 6: Effect of NH_3 concentration on reboiler duty at different capture rates

2. <u>Effect of EGR</u>

In this study, the effect of EGR was observed at the operating engine capacity of 85% load. With EGR, the engine power output was maintained to be similar to that without EGR in order not to compromise the availability of ship power on-board, as can be seen in Table 3. The effect can be seen in the reduced flue gas flow and increased concentration of CO_2, resulting in an increased efficiency of the capture process. The capture solvent flow quantity was lower for handling the reduced amount of flue gas and the reboiler duty decreased co-currently at different capture rates, as can be seen in Figure 8.

3.3 Cost calculations

In this work, the cost estimation is based on European Best Practice Guidelines for Assessment of CO_2 capture technology. [46,47] The cost of CO_2 captured was evaluated and used as a measure for the economic index, using the stated parameters in Table 4. The cost of CO_2 captured was calculated taking into consideration the capital expenditure (CAPEX), the fixed operational expenditure (FOPEX), and the variable operational expenditure (VOPEX) and the total amount captured annually. This was done for varying engine load values and different capture rates. A sensitivity analysis was also carried out to determine the effect of the quantity of captured CO_2 on the cost of capture.

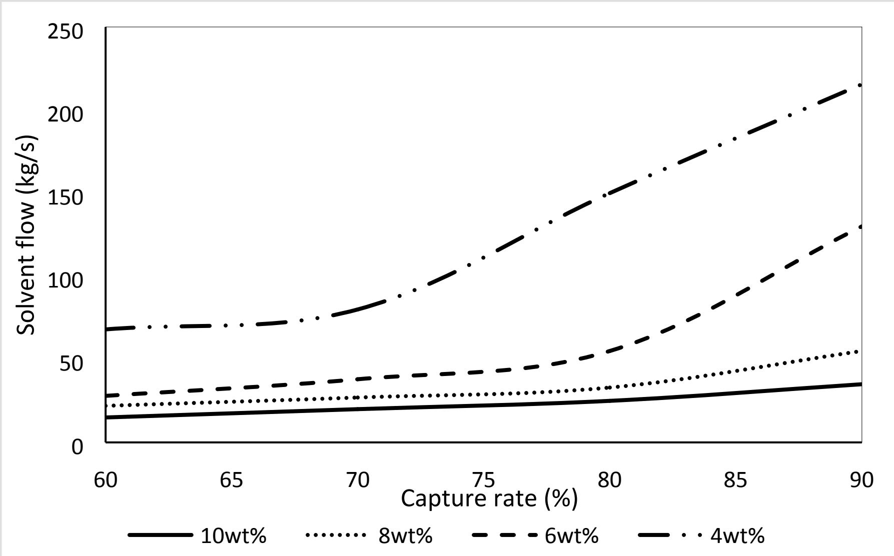

Figure 7: Effect of NH_3 concentration on solvent flow at different capture rates.

Table 3: 85% engine load with and without EGR

Parameter	**Without EGR**	**With EGR**
Recycled flow (kg/s)	-	5.22
Fresh air flow (kg/s)	15.9	11.85
Flue gas (kg/s)	16.35	12.20
CO_2 conc (%wt)	0.07	0.11
Power	9855.37	9856.70

1. CAPEX

The CAPEX includes the total equipment cost (TEC), the total direct plant cost (TDPC), the indirect plant cost (TIPC), and the fixed capital investment (FCI). The Aspen® Plus (V10) Economic Analyser was used to determine the TEC (latest cost basis available, dated first quarter of 2016). In this work, the TEC is used to estimate the costs of construction of both the capture and liquefaction processes. Direct construction costs include instrumentation and controls, piping, electrical equipment and materials, civil works, erection, steel structures and painting. For the purposes of this study, the civil works are assumed to be the increased new-build cost of the ship. Indirect construction costs include the yard improvements, service facilities, engineering, supervision and construction. Eqs. **(2) - (5)** show how the TDPC, TIPC, FCI and the CAPEX were estimated. [47]

$$TDPC = 2.10 * TEC \tag{2}$$

$$TIPC = 0.14 * TDPC \tag{3}$$

$$FCI = TDPC + TIPC \tag{4}$$

$$CAPEX = \frac{FCI}{0.8} \tag{5}$$

The annualised CAPEX is the total CAPEX multiplied by the capital recovery factor (CRF), Eq. (6), and it can estimated from Eq. (7) (6) below, as Eq. (7). The assumed project lifetime is 25 years (n) and the interest rate is 8% (i).

$$CRF = \frac{i(i+1)^n}{(i+1)^n - 1} \tag{6}$$

$$Annualized\ CAPEX = CAPEX * CRF \tag{7}$$

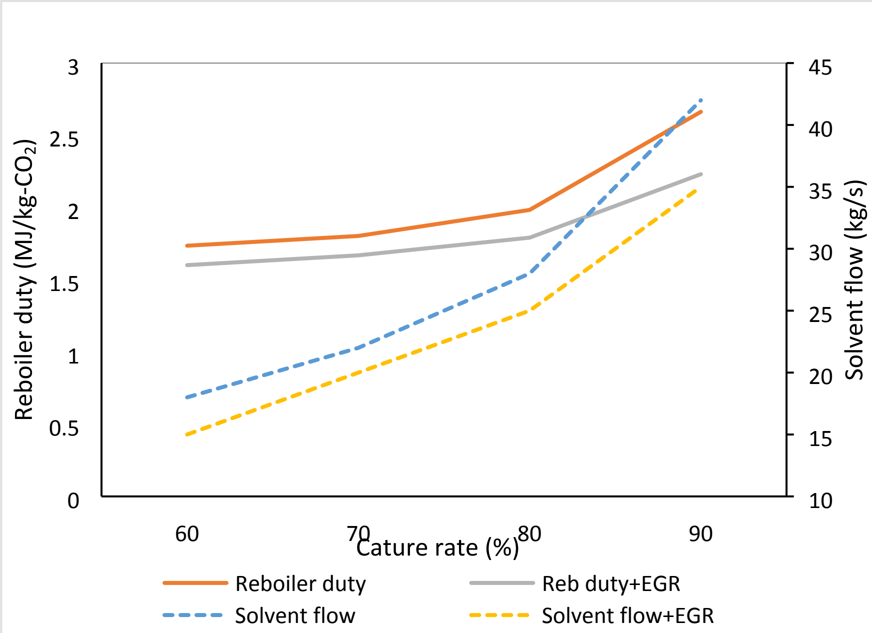

Figure 8: Effect of EGR on the capture process at varying capture rates

Table 4: General input for economic model

Parameter	Units	Value	Source
NH_3 price	$/tonne	451	[48]
LNG fuel price	$/tonne (£/tonne)	358.35 (282)	[22]
Sailing operational profile per year	%	0.57	[18]
Lifetime of the ship	years	25	[17]
Interest rate	/year	0.08	[17]
LNG consumption power	kg/kWh	0.151	[18]
Average time per crossing (round trip)	h	120 (240)	-
Number of round trips per year	-	30	-

2. FOPEX

This refers to the operating costs that are fixed for the plant irrespective of the engine load, and they include long-term service arrangement costs, overhead costs, operating and maintenance cost, etc.[17] They are generally related to the maintenance and labour cost. [47] This can be simply calculated from Eq. (8).

$$FOPEX = 0.03 * Annualised\ CAPEX \tag{8}$$

3. VOPEX

The VOPEX is related to the usage of raw materials and the electricity demand of the capture plant. It was assumed that an additional I MWe was provided on-board to meet the electrical demand for both the capture and liquefaction plants. The cost for extra fuel consumption was calculated based on this assumption. The solvent make-up cost was calculated by multiplying the unit price by the results obtained from the Aspen® Plus simulations for each case. Finally, the cost of captured CO_2 (CCC) was calculated by dividing the total annual cost (TAC) (Eq. (**9**)) by CO_2 captured annually, expressed in Eq. (**10**).

$$TAC = Annualised\ CAPEX + FOPEX + VOPEX \tag{9}$$

$$CCC = \frac{TAC}{CO_2\ captured\ annually} \tag{10}$$

3.3.1 Sensitivity analysis

1. Variation of capture rate

In this study, the effect of varying the capture rate was observed at the operating engine capacity of 85% load. Cost estimation was carried out for this case with and without EGR; with the EGR, the capture rate was varied from 60-90%, respectively. The cost of carbon capture obtained was higher for the case without EGR due to the higher flow of flue gas into the capture process as seen in Table 5. Figure 9 shows the total annual cost in terms of capture rates. It can be observed that the total cost (M$/a) varies linearly with CO_2 capture rate. As the capture rate increases, the amount of solvent required to meet the target increases, resulting in the increment of the variable cost. The cost of capture decreases as the capture rate is increased showing the effect of scale. It was found that at 60% capture rate (with EGR), the cost of capture obtained was $149/t, which is higher than at 90% capture rate (with EGR), $117/t.

Table 5: Economic estimation results

Description	No EGR	With EGR
CO_2 captured (tonne/a)	17380	16372
Annualised CAPEX (M$/a)	1.413	1.194
Fixed OPEX (M$/a)	0.043	0.036
Variable OPEX (M$/a)	0.804	0.679
Total (M$/a)	2.26	1.909
CCC ($/tonne CO_2)	130	117

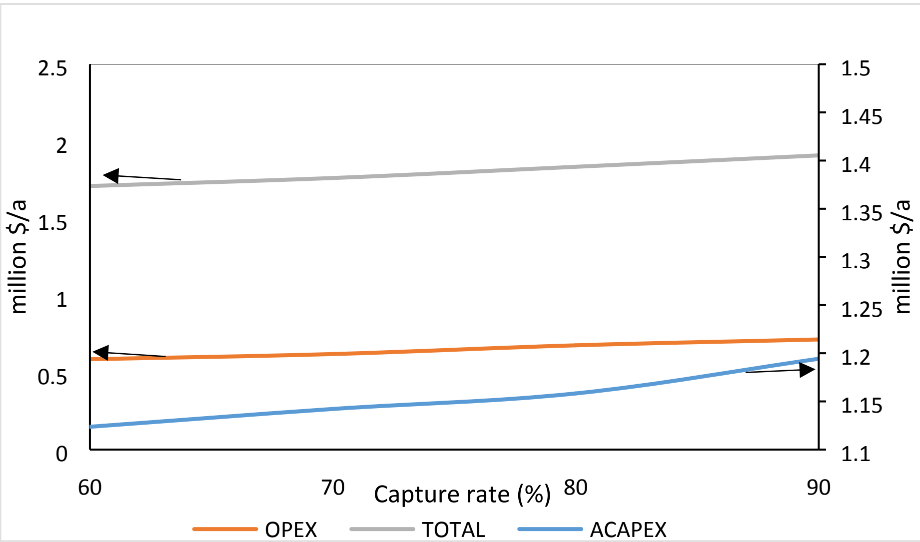

Figure 9: Total annual cost including the capital and operating cost with EGR, different capture rates

2. Variation of engine load (capacity)

Three different engine loads were analysed for this study; it was assumed to operate at 85%, 75% and 50% of engine full capacity while sailing, manoeuvring and hoteling, respectively. Detailed cost estimation was carried out at 85% load and then adapted for other conditions. At decreasing engine capacity other than full load, the amount of fuel reduces, thereby decreasing the total amount of CO_2 that can be captured. In this work, the CAPEX and FOPEX were kept constant at the base scenario, 85% load, but the VOPEX changes (fuel cost and solvent make-up rate) depending on the different engine capacity per time. All other parameters remained constant. The running VOPEX at 75% and 50% engine load decreased and was approximately 90% and 70% of the variable operating cost at 85% load, respectively. It was also observed that the cost of CO_2 capture increased at 75% and 50% load to $149/t and $217/t; therefore, the system is more efficient at 85% load, for which it was designed. In essence, determining the engine capacity at which the ship operates most often is important, and the capture system should be sized for that capacity to avoid increased costs.

3. Variation of fuel cost

The price of fuel is very important in the determination of the cost of capture. This case was analysed at the same basis as the variation of engine load case. The price of LNG for the base case scenario was chosen to be $358/t (£282/t) and converted using an exchange rate of 1.27(£/US$).[22] The cost was varied from $100-1000/t to observe the effect on the cost of capture. It can be observed that at the price of $1000/t, the cost of capture increased by approximately 21% compared to the base scenario of 50% load as seen in

Figure **10**. The increase in the LNG price results in the cost of capture increasing and vice versa.

4. <u>Variation of solvent cost</u>

The solvent cost is a key parameter that affects the economics of the capture process. This is important because the loss of solvent frequently occurs as a result of volatility, degradation and fugitive emissions. Therefore, feeding fresh solvent is required to make up for all the losses and, as a result, can increase or decrease the cost of capture. For this case, all parameters remained constant as in the variation of engine load case, apart from the cost of NH_3. The cost of NH_3 was varied between $100-900/t, and it was observed that the cost of capture ($/a) varies linearly with the price of NH_3 as shown in Figure 11.

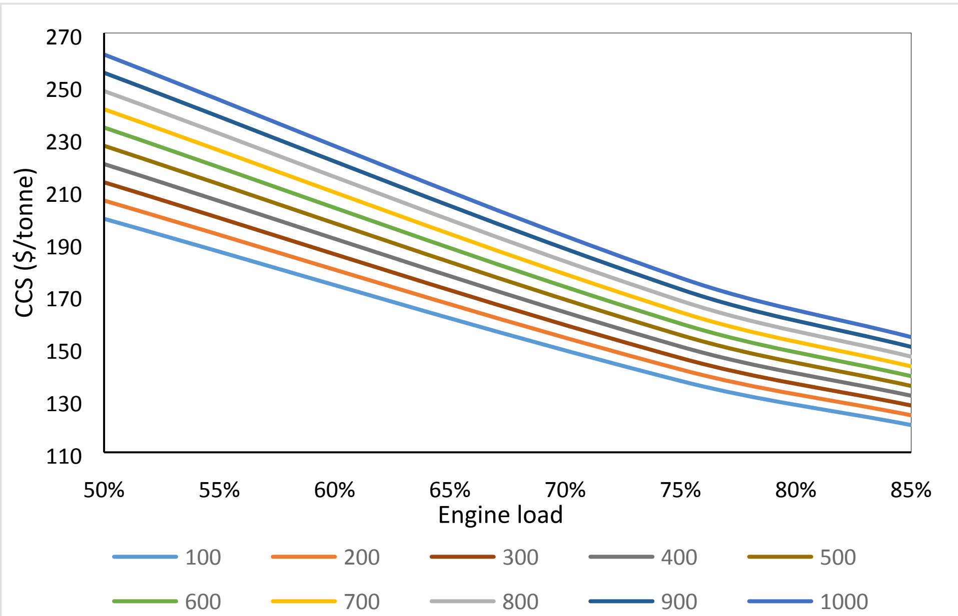

Figure 10: Effect of fuel cost on the cost of capture

3.4 Storage tank capacity

In this work, it was assumed that the captured CO_2 after liquefaction was injected into the CO_2 cargo tanks. If it is a non-CO_2 carrier, an additional storage tank must be provided on-board. The size of the vessel considered for this analysis was 20550 m^3 with an ullage of 10%. The ship leaving port is considered to be not filled to the maximum to accommodate the injected CO_2 on-board the ship as well as for safety and inspection purposes. For this case study, at 85% load without EGR, the liquefied CO_2 would occupy 314 m^3 (approximately 1.5%) of the cargo tank capacity per round trip when sailing. The BOG was not considered in this case. Therefore, the maximum filling capacity of the cargo tank would be 85-88%. In the analysis stated, the tank volume required is 314 m^3, but for safety reasons and assuming the ullage percentage, the storage capacity or volume can be increased by 20%. In a scenario where there is not enough space on-board the ship for CO_2 storage, smaller tanks can be used and unloaded in intermediate ports and reloaded with empty tanks.

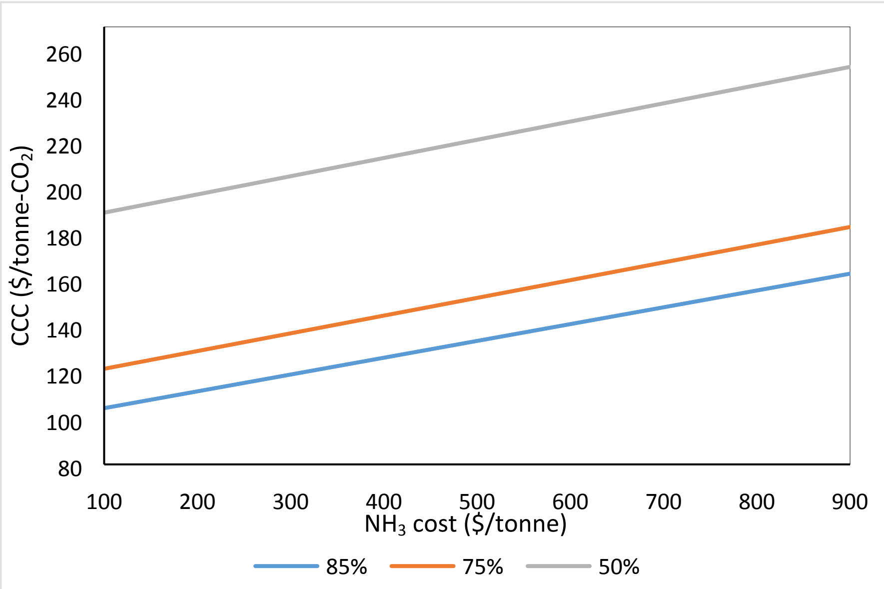

Figure 11: Effect of solvent cost on the cost of capture

3.5 Carbon tax

It is reasonable to conclude that this is the right time to consider the implementation of an international maritime carbon price as there is no charge yet for marine GHG emissions, but there will be.[49] A carbon price must be high enough to make renewables and low-carbon technologies competitive with fossil fuels.[50] A carbon price as high as $250 per tonne of fuel would likely lead to complete decarbonisation by 2035.[51] With the IMO 2050 target to cut CO_2 emissions, a carbon tax introduced for carbon-based fuels can promote positive behavioural measures such as improvements in operational and technical design efficiency, and also raise significant revenues.[49] Although, the idea of carbon tax was rejected by the International

Chamber of Shipping when proposed by the Organisation for Economic Co-operation and Development to raise revenue for climate change mitigation in 2015. [52] Market distortions, negative impacts on the global maritime trade, and a possibility that the raised funds may not be used to reduce CO_2 emissions from the maritime sector were cogent reasons stated for the rejection.[52] In this work, a carbon tax of $30/t CO_2 was assumed to be imposed, and at 85% load engine capacity, 17,380 t/a of CO_2 was captured. With a carbon capture system installed on-board, at 90% capture rate, a shipping company could save $521,386 annually. Installing the process on-board a ship can save shipping companies or owners a substantial amount of money in the future even with uncertain regulations and policies.

4 CONCLUSIONS

This study presented the application of ammonia-based solvent for carbon capture technology on-board for LNG-fuelled CO_2 ships. First, a dual-fuel ship energy system was modelled and validated. A hot-side heat integration consisting of the exchange of thermal energy between the exhaust gas, that would otherwise be wasted, and a reboiler were considered. Secondly, a rate-based model was developed for the capture process and validated with the Munmorah pilot plant data, obtaining very similar results, and then further scaled up to handle the flue gas from the ship energy system. Thirdly, the cold energy was used to re-liquefy the captured CO_2 into the cargo tank. The fuel option discussed here is natural gas as compared to conventional fuels such as heavy fuel oil. The effect of EGR was also analysed on the cost of capture, and this was found cheaper than without the implementation of EGR. The implementation of EGR accounted for 10% reduction in the cost of capture and a significant reduction in the power requirement for the CCS system. The additional engine cost that could be incurred from the implementation of EGR was not taken into account for this study.

In the integrated ship model performance, the cost of CO_2 captured was used as an economic index in this study. It was analysed at different operating loads (50%, 75% and 85%) and capture rates (60-90%). It was found that for the ship on-board capture to be optimal, it must be performed at the design specification. The capture process was optimised by determining the optimum solvent concentration that could result in minimum reboiler duty, and was found to be at 10 wt% ammonia concentration based on the parameters chosen. At the capture level of 90%, the cost of capture ($117/t) was found to be cheaper than at 60% ($149/t); also, the cost of capture without EGR was higher than when compared with EGR. Other sensitivity analyses such as the variation of engine load, fuel cost and solvent cost were also considered. Storage analysis was also determined for liquefied CO_2 injection into the cargo tanks for CO_2 carriers and into supplementary tanks for non-CO_2 carriers.

In general, increasing the capture rate and integrating EGR decreased the cost of capture for this case study. It can be concluded that the capture design rate should be as high as possible to reduce cost. In terms of the different engine loads, the operational profile of the specific ship must be studied before designing the ship-based capture system. For this study, it was varied at three engine loads, and an increase in the capture cost was observed as the load decreased. Finally, other dynamic capture process operations could be adapted in future by considering varying the engine load to reduce cost. The effect of the ship motion was not considered in this work, but again can be included in future studies. Membrane capture might also be of interest. Another potential cost reduction, specifically related to the space requirement on-board, is the application of process intensification concepts such as rotating packed beds. The cost of capture and size of the capture equipment could then be reduced significantly. [17]

ASSOCIATED CONTENT

The supporting information is available free of charge on the ACS Publications website at https://pubs.acs.org/

> Elemental analysis of liquefied natural gas; New exhaust gas data at varying loads for the capture and liquefaction system; Effect of EGR on fresh air flowrate into the main engine at 85% load; Base-case parameters of the developed capture plant; Stream conditions for the developed capture process; Simulation results for the BOG and captured CO2 compression and liquefaction cycle

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All authors have given approval to the final version of the manuscript

Notes

The authors have no competing financial interest

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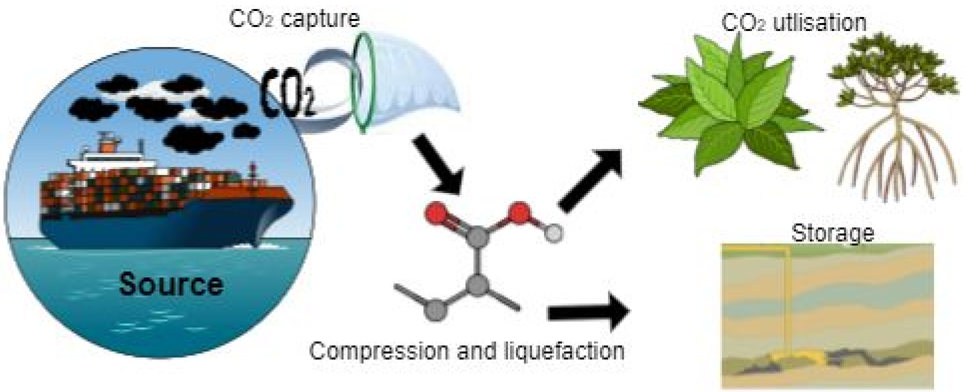

Process and economic evaluation of an on-board capture system for LNG-fuelled CO2 carriers

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