RESEARCH ARTICLE
DOI: 10.54926/jnamt.2026.2527
J Nav Architect Mar Technol 2026;228:24-31

An Investigation on the Effects of Different Solvents on the Characteristics of a Carbon Capture System in a Tanker

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To cite this article: F. Böbür, E. Güler, and S. Ergin. An investigation on the effects of different solvents on the characteristics of a carbon capture system in a tanker. *J Nav Architect Mar Technol*. 2026;228:24-31.

Received: 28.09.2025 - **Revision Requested:** 21.11.2025 - **Last Revision Received:** 22.12.2025 - **Accepted:** 21.01.2026 - **Publication Date:** 04.02.2026

Abstract

Harmful emissions into the atmosphere, such as carbon dioxide (CO_2), are increasing due to the extremely use of fossil fuels in the world. The shipping also increases global CO_2 emissions. This results in critical ecological issues like global warming, climate change and air pollution. Therefore, applications to reduce CO_2 emissions are needed, and carbon capture is one of these. In this study, the effects of mono-ethanolamine (MEA), piperazine (PZ) and ammonia (NH_3) solvents on the carbon capture costs and CO_2 capture rates (%) of the carbon capture system aboard a tanker were investigated for 30 wt% solvents. Capturing performance and economic analyses of the carbon capture system aboard the 49.990 DWT tanker were performed using Aspen HYSYS software. For different solvents, annual captured CO_2 emission amounts and CO_2 capture rates (%) were obtained at 85% engine load-cruise mode. For the same geometries of carbon capture columns, the carbon capture costs of the system per ton of CO_2 are \$82.6, \$69.6, and \$47.3 for MEA, PZ and NH_3 solvents, respectively and the CO_2 capture rates are 30.9%, 36.7%, and 54% for MEA, PZ and NH_3 solvents, respectively. Cost-effective capture of CO_2 emissions released from ships into the atmosphere is important for the widespread use of carbon capture and storage systems.

Keywords: Carbon capture and storage, decarbonization, CO_2 emission, tanker, solvent

1. Introduction

Harmful emissions emitted into the atmosphere by usage of fossil fuels are increasing because of increasing energy need for various industries and home usage. Approximately 87% of carbon dioxide (CO_2) production resulting from human activities is the result of burning fossil fuels [1]. Thus, this causes adverse consequences like global warming, climate change, and air pollution. The shipping sector has a share of over 80% of the goods transported by volume on global trade. Also, its proportion of greenhouse gas (GHG) emission to global GHG emission is approximately 3% [2]. GHG emissions from ships are going up due to the increasing dimensions of ships and fleets even though GHG emissions by maritime industry have small share among other transportation modes and industries. Some regulations, such as the Ship Energy Efficiency Management Plan (SEEMP) and the Energy Efficiency Design Index (EEDI) were launched in amendments to *International Convention for the Prevention of Pollution from Ships*-MARPOL Annex VI by the International Maritime Organization (IMO) [3]. The target of the EEDI is to make ships energy-efficient in the

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design phase by optimizing their hull form and decreasing electric consumption by operational measures. The SEEMP aims to improve ships' energy efficiency and optimize the operational performance of ships by operational adjustments, such as installing waste heat recovery (WHR) equipment, optimizing the speed of ships, and weather routing. Also, the SEEMP is obligatory for ships above 400 gross tonnages [3]. The Energy Efficiency Existing Ship Index (EEXI) is another regulation by the IMO about enhancement of ships' energy efficiency. The target of the EEXI is to enhance the energy efficiency of ships already in operation and decrease GHG emissions from shipping [4]. The Carbon Intensity Indicator (CII) is another regulation by the IMO regarding the evaluation of GHG emissions on the volume of loads and miles transported. Also, the required annual reduction factor to be met by a ship on her operations is determined by the CII and the efficiency categories are A, B, C, D, and E for a ship [5]. The Monitoring, Reporting and Verification system is a regulation by the European Union (EU) to assess CO_2 emissions from ships by monitoring and reporting fuel consumption and CO_2 emissions of ships per voyage and on yearly basis, based on ships above 5000 gross tonnes at European Economic Area (EEA) ports. Companies from shipping industry must submit a monitoring plan for each ship and the data collected must be verified by accredited third parties [6]. This regulation is significant to increase the transparency and awareness of GHG emissions from shipping for decreasing fuel consumption and emissions. The IMO aims to reach a 20% reduction by 2030 and a 70% reduction by 2040 in GHG emissions, compared to 2008 level. Also, IMO aims to have net zero emissions by 2050 [7]. Moreover, the EU has target to decrease GHG emissions by 55%, based on the 1990 level, by 2030. This is evaluated economically feasible and beneficial by the EU [8]. Therefore, decarbonization of ships and carbon capture and storage (CCS) have become significant working fields to be considered [9].

There are many studies regarding CCS in the literature. Van Duc Long et al. [10] conducted a marine CO_2 capture study on a 3000-kW diesel engine with different configurations to evaluate CO_2 removal performance of the systems. Mono-ethanolamine (MEA), MEA/piperazine, (MEA/PZ) and n-methyl-diethanolamine/PZ are considered as solvents in this study. The results revealed that the CO_2 removal performance of proposed configuration was obtained as 94.7% and there is an increase of 8.4% in comparison with the base case. Tavakoli et al. [11] studied about the feasibility of carbon capture onboard ships. Retrofit and newbuild ships are considered for assessment the technical feasibility using the solvent-based post-combustion capture in this study. The results indicated that limited space and additional power required are challenges for the retrofit case. Also, it is challenging to find adequate space for CO_2 storage in terms of cargo capacity. Brandl et al. [12] conducted a study to obtain the hypothetical solvent to achieve the cost reduction by comparing the performances of various solvents. The results showed that a 65% of cost reduction was achieved and a cost limit of \$26/ton CO_2 (\$: US Dollars, weight unit: ton) was obtained. Zhou et al. [13] conducted a study on the carbon capture specifications of the exhaust gas of a marine engine. In this study, a K_2CO_3 solution was used in the simulation of CO_2 capture from the exhaust gas using ASPEN Plus. Various activators used in the experiment were selected using simulation results. The results showed that the absorption rate of CO_2 from the exhaust gas of the marine engine can be improved by a small amount of activator. Mao et al. [14] conducted a study on a mixed absorbent on the marine carbon capture. The characteristics of absorption and desorption were evaluated for different mole ratios. The results indicated that the average CO_2 absorption rate increased by 48% in comparison with MEA. Güler and Ergin [15] conducted a study on a solvent-based CCS system. Various types of ships are considered to investigate the performance of a system and to analyze its cost for different ships in this study. The results showed that the CCS system is more economic than other CO_2 control methods for ships with high speed. Bayramoğlu [16] conducted a study about post-combustion carbon capture on a marine engine. WHR and carbon capture system are considered to examine the rate of carbon reduction and the EEDI for ships. In this system, there is a 14% reduction of EEDI by WHR, and by 90% with the carbon capture. The results indicated that the carbon capture can be a promising method to meet the regulations.

There is no such study has investigated the effects of various solvents on capturing and economic performance of a solvent-based CCS system aboard a tanker by considering the actual general arrangement of a ship in the literature. Available space of the general arrangement of the ship is evaluated for the system because there is limited space for the columns of the system onboard the ship. The aim of this study is to investigate the effects of various solvents on the annual amount of the CO_2 emission captured and CO_2 capture rate (%) at the engine load of 85%, cruising mode. The other objective is to compute the carbon capture cost of the system per ton of CO_2 captured for different solvents. A 49,990-DWT tanker was examined in this study. MEA, PZ and, ammonia (NH_3) were considered as solvents.

2. Mathematical Model of CCS System

2.1. Carbon Capturing Model

Capturing performance analysis of the solvent-based CCS system aboard a tanker is conducted by using ASPEN software. The CCS system is modeled. MEA, PZ and, NH_3 are considered as solvents in this study. MEA is a common solvent and its some advantages are low volatility and relatively fast kinetics. However, its some disadvantages are high oxidative degradation and relatively high energy demand [17]. PZ has fast kinetics and low degradation rate [10]. Also, it has high thermal stability and less volatility in comparison with conventional amine-based alkanolamine [18]. NH_3 has a lower heat of reaction for absorption of CO_2 compared to MEA and the disadvantage of NH_3 is its volatility [19]. Furthermore, NH_3 is highly corrosive, and metal materials should be protected from contact with it. NH_3 is a toxic substance, and prolonged exposure to it should be avoided for health reasons. Additionally, fast kinetics, less tendency to degradation, less corrosive and less toxicity are some of the criterion on solvent selection for solvent-based CCS system [20]. In the process of absorption of CO_2 by the MEA solution, following chemical reactions take place, as shown in Equations (1-5) [15]:

$$\mathrm{MEACOO^- + H_2O \leftrightarrow MEA + HCO_3^-} \tag{1}$$

$$\mathrm{CO_2 + 2H_2O \leftrightarrow HCO_3^- + H_3O^+} \tag{2}$$

$$\mathrm{HCO_3^- + H_2O \leftrightarrow CO_3^{-2} + H_3O^+} \tag{3}$$

$$\mathrm{MEAH^+ + H_2O \leftrightarrow MEA + H_3O^+} \tag{4}$$

$$\mathrm{2H_2O \leftrightarrow H_3O^+ + OH^-} \tag{5}$$

MEA solution is a benchmark to compare capturing performance due to its reaction rate [10]. In absorption of CO_2 by the PZ solution, following reactions occur, as shown in Equations (6-10) [18]:

$$\mathrm{H_2O \leftrightarrow H^+ + OH^-} \tag{6}$$

$$\mathrm{PZH^+ \leftrightarrow PZ + H^+} \tag{7}$$

$$\mathrm{PZ + CO_2 \leftrightarrow PZCOO^- + H^+} \tag{8}$$

$$\mathrm{PZCOO^- + CO_2 \leftrightarrow PZ(COO^-)_2 + H^+} \tag{9}$$

$$\mathrm{H^+PZCOO^- \leftrightarrow PZCOO^- + H^+} \tag{10}$$

Chemical equilibrium constants for the PZ solution reactions are calculated [18]. For NH_3, following reactions occur, as shown in Equations (11, 12) [19]:

$$\mathrm{CO_2 + OH^- \leftrightarrow HCO_3^-} \tag{11}$$

$$\mathrm{NH_3 + CO_2 + H_2O \leftrightarrow NH_2COO^- + H_3O^+} \tag{12}$$

Chemical equilibrium constants for the NH_3 solution reactions are calculated [19]. The annual amount of the CO_2 emissions emitted from the ship into the atmosphere and CO_2 capture rate (%) are required to compute the annual amount of the CO_2 captured by the system. The annual amount of the CO_2 emission emitted from the ship [t] is computed by using specific fuel oil consumption (SFOC) [g/kWh], power [kW], emission factor (EF), and annual operational time [h] of the main engine, as shown in Equation (13).

$$\text{Annual } CO_2 \text{ emission=SFOC*Power*Annual operational time*EF} \tag{13}$$

CO_2 capture rate (%) is the ratio of the CO_2 transferred from the stripper to CO_2 storage onboard to captured CO_2 by the absorber. The annual amount of the CO_2 captured by the system is calculated by using the annual amount of the CO_2 emission emitted from the ship into the atmosphere and CO_2 capture rate (%), as shown in Equation (14).

$$\text{Annual } CO_2 \text{ captured=Annual } CO_2 \text{ emission*} CO_2 \text{ capture rate} \tag{14}$$

2.2. Economic Model

The carbon capture cost of the system per ton of CO_2 captured (C_{PCC}) was obtained for different solvents in economic analysis. The equipment and its installation cost (C_{EI}) and the other capital cost (C_O), such as engineering services and commissioning, are calculated using ASPEN software. The total capital cost (C_T) is calculated by the sum of the equipment and its installation cost (C_{EI}) and the other capital cost (C_O), as shown in Equation (15).

$$C_T = C_{EI} + C_O \tag{15}$$

The annualized total capital cost (C_{AT}) is computed by using C_T and the capital recovery factor (CRF), as shown in Equations (16, 17). The life of a ship is assumed as 25 years (n) and interest rate (i) is assumed as 10% without inflation [21].

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{16}$$

$$C_{AT} = C_T CRF \tag{17}$$

The annual operational cost (C_{AO}) is calculated by using the freight loss cost (C_{FL}) due to the weight of the CCS system and additional fuel consumption cost (C_{AFC}) due to the additional power need for the system, as shown in Equation (18).

$$C_{AO} = C_{FL} + C_{AFC} \tag{18}$$

The annual life cycle cost (C_{ALC}) is calculated by using the annualized total capital cost (C_{AT}) and the annual operational cost (C_{AO}), as shown in Equation (19).

$$C_{ALC} = C_{AT} + C_{AO} \quad (19)$$

C_{PCC} is the ratio of the annual life cycle cost (C_{ALC}) to the CO_2 captured annually (T_{CCA}), as shown in Equation (20).

$$C_{PCC} = \frac{C_{ALC}}{T_{CCA}} \quad (20)$$

3. Specification of The Tanker, Selected Solvents and The CCS System

3.1. Specification of the Tanker

In this study, the ship considered and her properties of the diesel main engine at various engine loads are given in Tables 1 and 2.

EFs for a slow-speed marine diesel engine are used in this study. EFs are 3170 kg/ton of fuel for CO_2, 7.4 kg/ton of fuel for CO, 87 kg/ton of fuel for NO_X and 54 kg/ton of fuel for SO_2 [22].

3.2. Properties of Selected Solvents

In this study, MEA, PZ and, NH_3 are considered as solvents. MEA's chemical formula is C_2H_7NO and its molecular weight is 61.1 g. Its density at 20 °C is 1016 kg/m^3, and its melting and boiling points are 4 and 167 °C, respectively [23]. PZ's chemical formula is $C_4H_{10}N_2$ and its molecular weight is 86.1 g. Its density at 50 °C is 1020 kg/m^3, and its melting and boiling points are 35-45 and 110 °C, respectively [23]. NH_3's chemical formula is NH_3 and its molecular weight is 17 g. Its density at 15 °C is 0.73 kg/m^3, and its melting and boiling points are -77.7 and -33.3 °C, respectively.

Table 1. The particulars of the ship [22].

Features	Value
Length overall	183 m
Beam	32.2 m
Draft	16.5 m
Deadweight	49,990 t
Installed power (main engine)	10,320 kW

3.3. Properties of the CCS System

In the CCS system, the CO_2 emissions from the exhaust gas of the main engine is captured in the absorber. The CO_2-rich solvent is directed to pump to transfer to heat exchanger, whereas the clean gas from the residual exhaust gas is released. CO_2-solvent mixture is directed to stripper after heating by the heat exchanger. CO_2 is separated from the mixture in the form of gas in the stripper by heating and transferred to the CO_2 storage tank on-board and liquefied. CO_2-solvent mixture without CO_2 is cooled by the heat exchanger to re-use and directed to absorber, as shown in Figure 1.

Additional power is required for CCS due to processes such as, heating, cooling, pumping, and liquefaction. Also, extra space is needed for CO_2 storage in ships. The dimensions of the absorber and the stripper, and the power of the heat exchanger, and the pump are significant on carbon capture rate, the cost per ton of CO_2 captured, and occupied area on a ship. CCS system has also effects on the stability of ships because of its extra weight, area and location at a ship and freight revenue because of decreasing the amount of goods transported. The main aim of the carbon capture systems is contributing to cleaner and more sustainable environment based on regulations regarding reduction in GHG emissions. The optimization of the cost and dimensions of these systems are important to use widely on ships. In this study, MEA, PZ and, NH_3 are considered as solvents. The carbon capture system is located at the near of the funnel of the ship [24].

Table 2. The properties of the main engine at various engine loads [22].

Load (% Maximum continuous rating)	Power (kW)	SFOC (g/kWh)	Exhaust gas mass flow rate (kg/s)	Exhaust gas temperature (°C)
100	10,320	176.4	23.4	255
95	9,804	175.1	22.4	248
90	9,288	174.1	21.7	243
85	8,772	173.3	20.9	239
80	8,256	172.7	20.1	236
75	7,740	172.3	19.1	235
70	7,224	172.2	18.2	235
65	6,708	172.5	17.1	237
60	6,192	173.0	16.1	240
55	5,676	173.9	14.9	244
50	5,160	174.8	13.8	250

SFOC: Specific fuel oil consumption

4. Results and Discussion

4.1. Capturing Performance Analysis

Capturing performance analysis is carried out by using ASPEN HYSYS package program in this study. Firstly, solvents and fluids considered in this study are selected in the component list. Then, the solution method is selected. Acid gas-chemical solvents package is used in this study. Additionally, acid gas-chemical solvents package is a method, which is developed with the Peng-Robinson equation of state for vapor phase. Afterwards, the components in this system are selected and the system is formed. Conditions, such as temperature, pressure, and mass flow rate, are determined in this system. Lastly, CO_2 capture rates are obtained for MEA, PZ, and NH_3 at the engine load of 85%, cruising mode. The temperature of 30 °C and the pressure of 102 kPa are used for all solvents in this study. The volumetric flow rates of these solvents are 150, 168 and 248 m^3/h for MEA, PZ, and NH_3 solvents, respectively. The diameter and height of the absorber and stripper columns, space available on the ship for the CCS system, annual operational time of the main engine of the ship, and CO_2 EF (g-CO_2/kWh) of the marine main engine are some key parameters in capturing performance analysis. In this study, the absorber and stripper columns' diameters are equal and 1.5 m according to the general arrangement of the tanker. Both absorber and stripper have 10 stages. Also, they are tray columns and tray spaces are 0.6 m. Mass transfer in these columns are computed using the mass, equilibrium, summation of vapor and liquid compositions and heat (MESH) equations by Aspen HYSYS software based on the equilibrium-based model [18]. Additionally, the composition of exhaust gas is modelled as nitrogen of 67%, CO_2 of 12%, water of 11%, and oxygen of 10% by weight, respectively [25]. The annual amount of the CO_2 emission emitted from the ship into the atmosphere at the engine load of 85%, cruising mode, for a duration of 6400 hours of operational time is calculated as 30,842 tons of CO_2. CO_2 capture rates are calculated as 30.9%, 36.7% and 54% for MEA, PZ and NH_3 solvents, respectively. Also, the annual amounts of CO_2 captured are obtained as 9,530 tons, 11,319 tons and 16,655 tons for MEA, PZ and NH_3 solvents, respectively. Annual CO_2 captured is maximum for NH_3 solvent because of higher CO_2 capture rate of NH_3 solvent compared to other solvents in this study, as shown in Figure 2.

4.2. Economic Analysis

Economic analysis is conducted for MEA, PZ and, NH_3 30 wt% (wt: percentage by weight) at the engine load of 85%, cruising mode. In the scope of this analysis, the carbon capture cost of the system per ton of CO_2 (C_{PCC}) is calculated using the system annual life cycle cost and the annual amount of the CO_2 captured by the system. The cost of the system consists of equipment, construction, buildings, engineering and supervision costs [26]. In this analysis, the share of this types of costs are 50.5%, 29%, 4.7% and 15.8%, respectively. The equipment and its installation cost (C_{EI}) is calculated as \$2,001,330 and the other capital cost (C_O) is \$516,067. The total capital cost (C_T) is \$2,517,397 and the CRF is calculated as 0.11 for the life of a ship of 25 years (n) and interest rate (i) of 10% without inflation. The annualized total capital cost (C_{AT}) is \$277,342. Also, the annual operational cost (C_{AO})

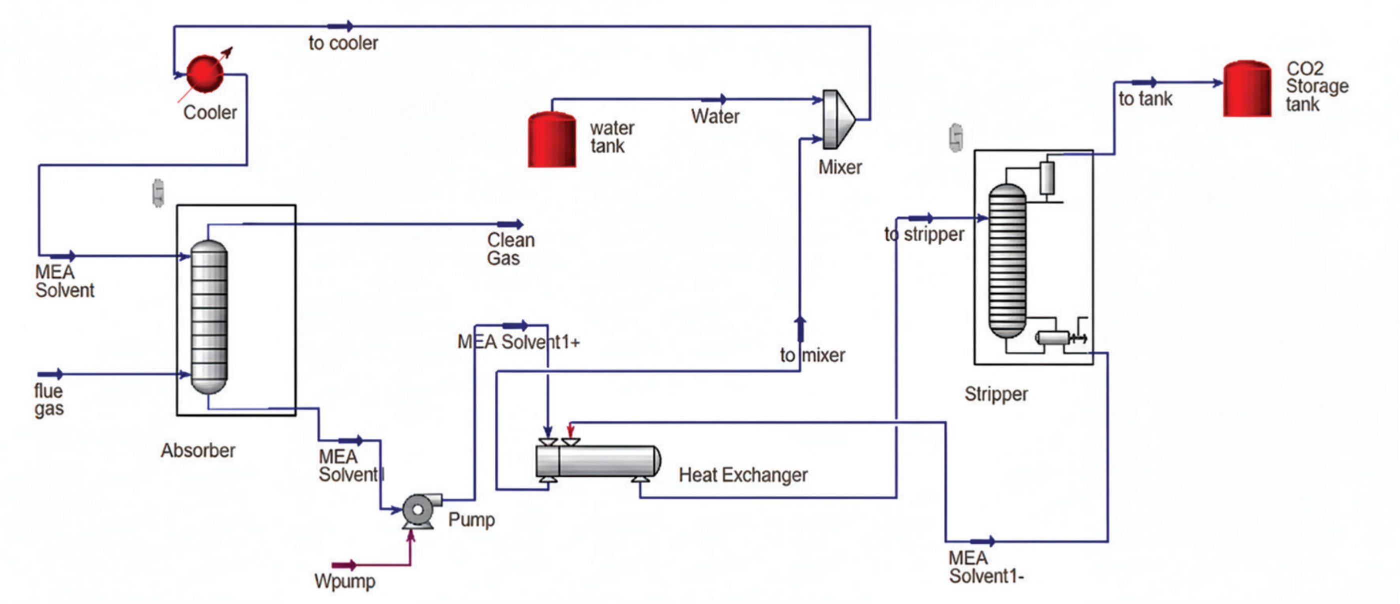

Figure 1. Schematic of CCS system considered in this study.

CCS: Carbon capture and storage, CO_2: Carbon dioxide, MEA: Mono-ethanolamine

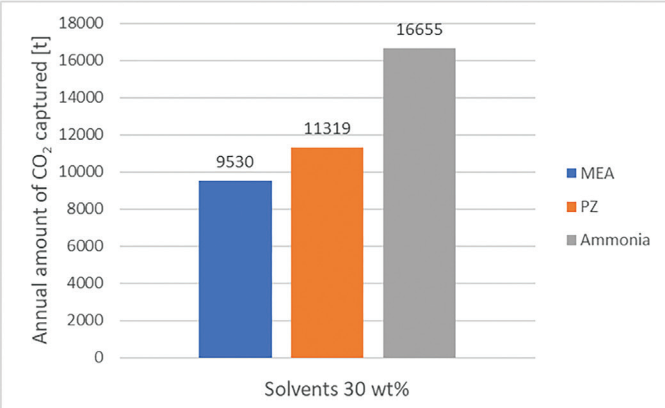

Figure 2. Relation between solvents and annual CO_2 captured by the CCS system.

CCS: Carbon capture and storage, MEA: Mono-ethanolamine, CO_2: Carbon dioxide, PZ: Piperazine

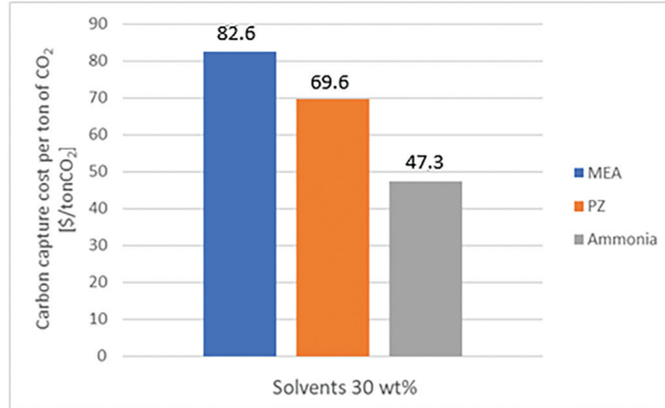

Figure 3. Relation between solvents and C_{PCC} of the CCS system.

CCS: Carbon capture and storage, MEA: Mono-ethanolamine, PZ: Piperazine

is calculated as $510,159 with the assumption of additional fuel consumption cost of the system for capturing the CO_2 emissions as 5% of the fuel consumption of the ship and freight loss cost as 10% of the sum of the equipment and its installation cost (C_{EI}) and the buildings cost [18]. Also, the annual life cycle cost (C_{ALC}) is calculated as $787,501, as shown in Table 3.

C_{PCC} is $82.6 for MEA solvent for the CO_2 capture rate of 30.9%, $69.6 for PZ solvent for the CO_2 capture rate of 36.7% and $47.3 for NH_3 solvent for the CO_2 capture rate of 54%, as shown in Figure 3.

C_{PCC} is minimum for NH_3 solvent because of higher annual CO_2 captured for NH_3 solvent compared to other solvents in this study. Moreover, the EU Emission Trading System (ETS) is a regulation set by the EU. With the ETS, ships pay for their emissions emitted into the atmosphere and the price is determined by the EU using the value of the amount of annual emission from ships and the EU ETS prices are shown in Figure 4.

Table 3. Cost components of the CCS system.

Features	Values
C_{EI}	$2,001,330
C_O	$516,067
C_T	$2,517,397
C_{AT}	$277,342
C_{AO}	$510,159
C_{ALC}	$787,501
CRF	0.11
n	25 years
i	10%

CCS: Carbon capture and storage, CRF: Capital recovery factor

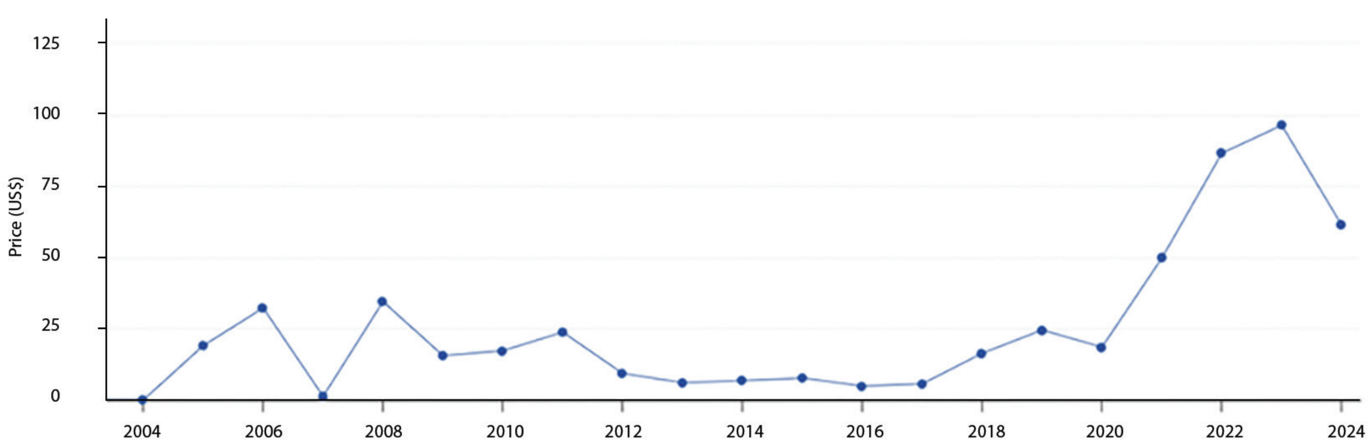

Figure 4. Trends in EU ETS between 2004 and 2024 [$/tonCO$_2$] [27].

EU: European Union, ETS: Emission Trading System

C_{PCC} for MEA and PZ in this study is higher than the EU ETS price in 2024. However, the cost for NH_3 is less than the EU ETS price in 2024. According to the new EU ETS II, carbon prices (in European Currency Unit) can go up €122/tCO_2 (\$144/tCO_2) in 2030 and a mean of €99/tCO_2 at the period of 2027 and 2030 [28]. In the near future, this technology can be considered economically feasible with increasing ETS prices and decreased C_{PCC} for ships. When C_{PCC} is higher than ETS and/or carbon tax, this is a barrier for these systems to be feasible for ship owners. Therefore, studies for the reduction of C_{PCC} are important for cleaner and sustainable shipping. Economic results from this study and the literature are given in Table 4.

Table 4. Economic results from this study and the literature.

Carbon capture cost (\$/tonCO_2)	References
149 (capture rate of 60%) 117 (capture rate of 90%)	[17]
70.34 (capture rate of 91%)	[29]
65.35 (capture rate of 34.5%)	[15]
77.50 (capture rate of 73%)	[21]
389 (capture rate of 60%) 296 (capture rate of 80%)	[30]
82.6 (capture rate of 30.9%) 69.6 (capture rate of 36.7%) 47.3 (capture rate of 54%)	From this study

According to Table 4, most of C_{PCC} from different studies are higher than the EU ETS prices. Therefore, the results in this study are consistent with various studies in the literature. Cost-effective reduction of CO_2 emissions released from ships into the atmosphere is important for the widespread use of carbon capture systems. Also, CCS on ships are important to reduce the adverse effects of the emissions of ships to the environment and human health.

5. Conclusion

The effects of MEA, PZ and NH_3 solvents on the carbon capture costs and CO_2 capture rates of the carbon capture system aboard a tanker were investigated for 30 wt% solvents in this study. Capturing performance and economic analyses of the CCS system aboard the 49.990 DWT tanker were performed using ASPEN HYSYS software. For different solvents, annual CO_2 emission amounts and CO_2 capture rates (%) were obtained at 85% engine load-cruise mode. The annual amount of the CO_2 emission emitted from the ship into the atmosphere at the engine load of 85%, cruising mode, for a duration of 6400 hours of operational time is calculated as 30,842 tons of CO_2. For MEA solvent 30 wt%, CO_2 capture rate is calculated 30.9% and the annual amount of CO_2 captured is 9,530 tons. Also, C_{PCC} is \$82.6 for MEA solvent 30 wt%. C_{PCC} is \$69.6 for PZ solvent 30 wt% for the CO_2 capture rate of 36.7% and the annual amount of CO_2 captured is 11,319 tons. Also, C_{PCC} is \$47.3 for NH_3 solvent 30 wt% for the CO_2 capture rate of 54% and the annual amount of CO_2 captured is 16,655 tons. C_{PCC} in this study for MEA and PZ is higher than the EU ETS price in 2024. Whereas, the cost for NH_3 is less than the EU ETS price in 2024. This technology can be considered economically feasible with increasing ETS prices and decreased carbon capture cost per ton of CO_2 captured for ships. CCS on ships are important to reduce the adverse effects of the emissions of ships to the environment and human health in order to have cleaner and sustainable shipping industry based on the IMO's net zero emissions target by 2050.

Acknowledgements

The authors thank the Turkish Scientific and Technological Research Council of Türkiye, TÜBİTAK (2224-A-1919B022507858) and Istanbul Technical University, BAP (FHD-2025-47373 and Project ID: 47929) for the financial support they received during their research.

Footnotes

Authorship Contributions

Concept: E. Güler, and S. Ergin, Design: F. Böbür, and E. Güler, Data Collection or Processing: F. Böbür, E. Güler, and S. Ergin, Analysis or Interpretation: F. Böbür, E. Güler, and S. Ergin, Literature Review: F. Böbür, E. Güler, and S. Ergin, Writing: F. Böbür, E. Güler, and S. Ergin.

Conflict of Interest: No conflict of interest was declared by the authors.

Financial Disclosure: The authors would like to thank İstanbul Technical University Scientific Research Projects Coordination Unit (BAP) for providing financial support to the project numbered 44432.

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