**Article:**

Luo, X. and Wang, M. (2017) Study of solvent-based carbon capture for cargo ships through process modelling and simulation. Applied Energy, 195. pp. 402-413. ISSN 0306-2619

https://doi.org/10.1016/j.apenergy.2017.03.027

# Study of solvent-based carbon capture for cargo ships through process modelling and simulation

Xiaobo Luo, Meihong Wang*

Department of Chemical and Biological Engineering, the University of Sheffield, Sheffield S1 3JD United Kingdom

Email: Meihong.Wang@sheffield.ac.uk

**Abstract:**

Controlling anthropogenic $CO_2$ emission is crucial to mitigate global warming. Marine $CO_2$ emissions accounts for around 3% of the total $CO_2$ emission worldwide and grows rapidly with increasing demand for passenger and cargo transport. The International Maritime Organization (IMO) has adopted mandatory measures to reduce greenhouse gases (GHGs) emissions from international shipping. This study aims to explore how to apply solvent-based post-combustion carbon capture (PCC) process to capture $CO_2$ from the energy system in a typical cargo ship and the cost degrees of different integration options through simulation-based techno-economic assessments. The selected reference cargo ship has a propulsion system consisting of two four-stroke reciprocating engines at a total power of 17 MW. The study first addressed the challenge on model development of the marine diesel engines and then developed the model of the ship energy system. The limitations of implementing onboard carbon capture were discussed. Two integration options between the ship energy system and the carbon capture process were simulated to analyse the thermal performance of the integrated system and to estimate equipment size of the carbon capture process. It was found that the carbon capture level could only reach 73% when the existing ship energy system is integrated with the PCC process due to limited heat and electricity supply for CCS. The cost of $CO_2$ capture is around 77.50 €/ton $CO_2$. With installation of an additional gas turbine to provide extra energy utilities to the capture plant, the carbon capture level could reach 90% whilst the cost of $CO_2$ capture is around 163.07 €/ton $CO_2$, mainly because of 21.41% more fuel consumption for the additional diesel gas turbine. This is the first systematical study in applying solvent-based carbon capture for ships, which will inspire other researchers in this area.

**Keywords:** CCS, Post-combustion carbon capture, Chemical Absorption, Onboard carbon capture, Marine propulsion engine, Process simulation

## 1 Introduction

### 1.1 Background

The rapid increase of atmospheric concentration of $CO_2$ since the beginning of the Industrial Revolution is the main cause for global warming and extreme climate conditions [1]. Therefore, reducing anthropogenic $CO_2$ emission from major emitters such as combustion of fossil-fuel is vital to achieve the target of limiting average global temperature increase to 2°C in 2050 [2].

Transport sector contributes second largest $CO_2$ emission [3]. Marine transport accounts for 11.17% of transport thus approximately 3% of total global $CO_2$ emission [4]. Fuels such as diesel have been used to drive ships since the 1870s and most marine vessels primarily burn fuels to produce power for propulsion, electricity generation and thermal energy for heating and hot water [5]. With the increase of population and business activities, ship is an increasingly popular transportation method for travel and industry goods. $CO_2$ emissions from ship transport are also predicted to rise to 1.6 billion tons by 2050 (See Fig. 1). Thus the International Maritime Organization (IMO) has adopted mandatory measures to reduce GHG emissions from international shipping [6]. An agreement was also reached for monitoring, reporting and verification of $CO_2$ emissions from ships throughout Europe [7].

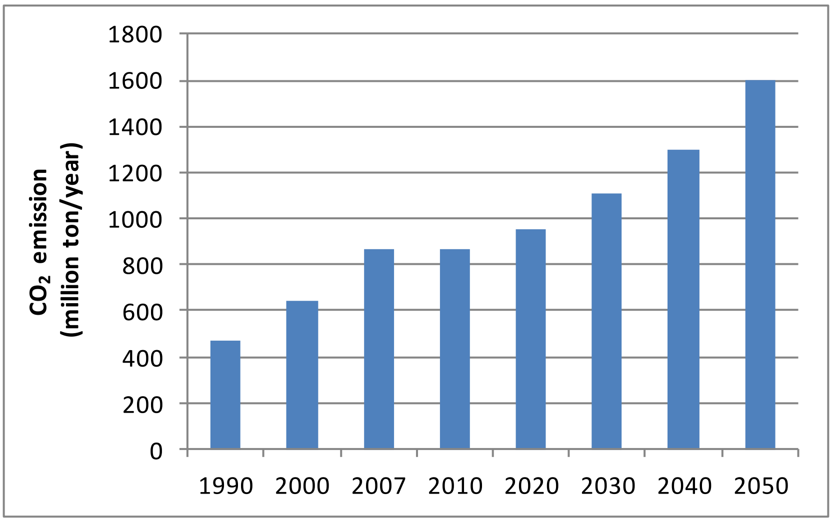


Fig 1. $CO_2$ emission trend from ships [8, 9]

### 1.2 Marine $CO_2$ emission reduction

There are several routes to improve thermal efficiency and to reduce $CO_2$ emission of ship to comply with the environmental protection demands such as optimal design of propulsion system [10, 11], replacement with cleaner fuels [12, 13], improving thermal efficiency through waste heat recovery [14, 15] and carbon capture and storage (CCS) [16].

For the alternative fuels route, liquefied natural gas (LNG) is an attractive condidate, which is widely regarded as a clean and reliable fuel for ship propulsion system. Its combustion emits much less waste gases such as $SO_x$ and $NO_x$ [12]. In addition, the $CO_2$ emission reduces around 25 – 30% because of low carbon to hydrogen ratio of the fuel. One disadvantage of LNG is that the LNG tanks occupy more space and account more weight than marine diesel oil (MDO) because of smaller density of LNG fuel [13, 17].

Waste heat recovery (WHR) technology was investigated massively as an approach to improve the thermal efficiency of ship energy system. The temperature of flue gases emitted from the engine is still as high as 350 °C, which provides enough temperature pinches to heat a cold process stream or to generate low pressure steam. Previous studies [18-22] conducted simulation and performance analysis of different circulated fluids in WHR system and the heat integrations with the flue gases and cooling system. Shu et al. [15] made a comprehensive review of the application of WHR system in ships.

Using solvent-based post-combustion carbon capture (PCC) technolgy to absorb $CO_2$ in the flue gases is another approach for ship $CO_2$ emission reduction. Solvent-based PCC was proven to be the most promising technology for carbon capture for onshore fossil fuel fired power plants by massive studies [23-26]. But significant challenges need to be addressed towards its onboad application because of the natures of marine vessels such as off-shore, constant move and space constraints. In a feasibility study conducted by Det Norske Veritas (DNV) and Process Systems Enterprise Ltd. (PSE), it was found that the carbon capture and storage (CCS) is feasible for marine vessels and the $CO_2$ emission can reduce by up to 65% [16, 27], but the report is not in public domain. Apart from this, there is no publication on this topic so far.

### 1.3 Aim of this study and its novelties

This paper aims to explore how to apply solvent-based post-combustion carbon capture (PCC) process to capture $CO_2$ from the energy system in a typical cargo ship and the cost degrees of different integration options by simulation-based techno-economic assessments. To serve this aim, the objectives of this study include (1) to develop a steady state process model in Aspen Plus® of ship energy system and to perform model validation; (2) to develop a steady state process model in Aspen Plus® of CCS system including MEA-based PCC process, $CO_2$ compression and tank storage; (3) to carry out techno-economic evaluations for the integration between ship energy system and the CCS system with and without an additional diesel gas turbine.

To the best knowledge of the authors, this paper presented the first systematical study in applying solvent-based carbon capture for ships, which contributes to an in-depth understanding for the deployment of CCS on ships. This study started from the modelling of the cylinder process of the marine diesel engine, the final models of the integrated system (energy system of a 35,000 Gt cargo ship integrated with a full function CCS system) were developed in Aspen Plus® at industrial scale. By carrying out simulation-based techno-economic evaluations for different integration options, this study answered key questions relevant with potential commercial deployment of solvent-based carbon capture on ships, including (1) what are the capture levels that could be reached for the integrated system with or without an additional utilities supply, (2) the selections of $CO_2$ compression and storage method, (3) the key design features, such as equipment size and process parameters of the CCS system, and (4) the cost degrees of different integration options.

## 2 Model development of ship energy system

### 2.1 Reference cargo ship

Table 1 shows the main characteristics of the selected reference ship, which is a middle size cargo ship. The ship has two 9L46 marine diesel engines from Wärtsilä to provide propulsion power of 17 MW and it also supplies 3MW$_e$ electricity by integrating three power generators. The fuel consumed by the engines belongs to heavy marine oil, which is further specified to be diesel in this study.

Table 1. Characteristics of the reference cargo ship [28]

| Item | Value |
|---|---|
| Size (Gt) | 35,000 |
| Length (m) | 220.0 |
| Beam (m) | 28.2 |
| Draft (m) | 7.0 |
| Propulsion engine | 2* Wärtsilä 9L46 |
| Deadweight (mt) | 12,500 |
| Propulsion power (MW) | 17.0 |
| Auxiliary power (MW$_e$) | 3.0 |

The sketch of the ship energy system can be seen in Fig. 2. There are three main parts including the propulsion system, auxiliary power generation and WHR system. The propulsion system consists of two four-stroke marine diesel engines, which are directly coupled with two ship propellers through respective gearboxes. Three electricity generators are also connected to the gearboxes to cover a part of electric power demand of the ship. There is one WHR system for each single train of propulsion engine. A typical WHR configuration is a single pressure steam cycle with a steam drum, an integrated heat exchanger and a steam turbine. The steam generated from the steam cycle goes to a steam turbine with a generator to produce another part of electricity.

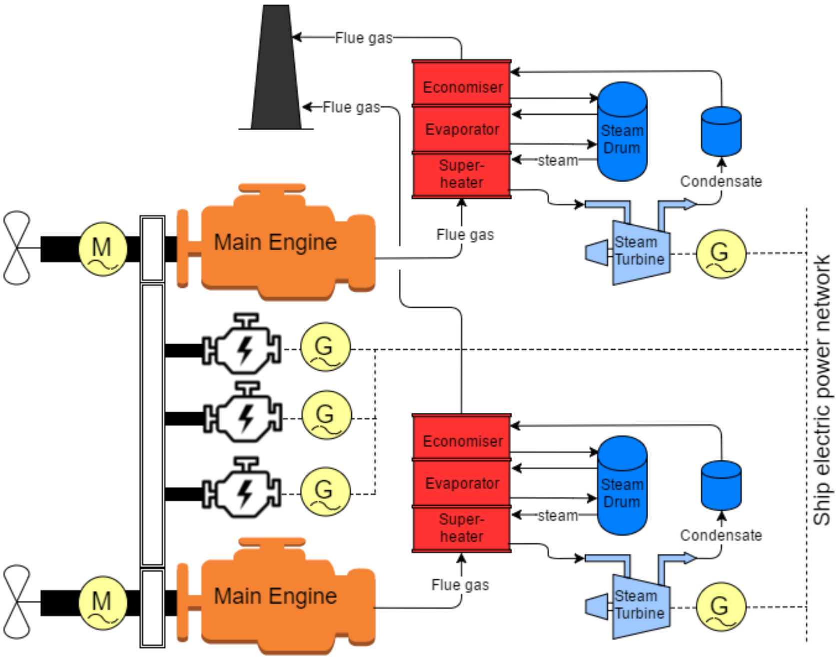


Fig 2. Sketch of ship energy system

## 2.2 Model development of marine diesel engine

### 2.2.1 Modelling of engine cylinder

The marine diesel engine converts the chemical potential energy of the marine fuel into mechanical energy driving the ship. Most modern ships use reciprocating diesel engines as prime mover considering operating simplicity, robustness and fuel economy compared with other prime mover mechanisms [29].

The key part of model development of marine diesel engine is modelling of thermal process inside diesel engine cylinders. There are two major challenges: (1) the thermal process happening in cylinders includes several unit processes including compression, combustion and expansion; (2) it is a reciprocating movement with dynamic work output.

In the model, this process was divided into three main units which are compression, combustion and expansion. The flowsheet of engine cylinder model in Aspen Plus$^{®}$ is displayed in Fig 3. The PR-BM property method (Peng-Robinson equation of state with Boston-Mathias modifications) is used for the properties prediction. The compression and expansion have been simulated using Compr blocks in Aspen Plus$^{®}$. The Compr block can be used to model polytropic centrifugal or positive displacement compressors and isentropic compressors or turbines. The combustion section was modelled as RGibbs block. The pressure of combustion was set at 2.4 MPa, which is the mean pressure of the diesel engine.

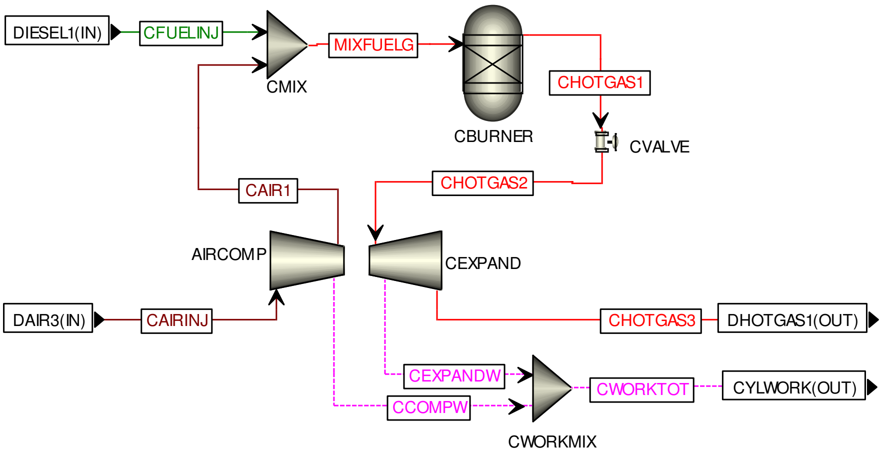


Fig 3. Modelling of single engine cylinder in Aspen Plus®

### 2.2.2 Modelling of marine diesel engine

In addition to the engine cylinders, the diesel engine has a fresh air intake system, fuel injection system and a cooling system. The flowsheet of the diesel engine is shown in Fig. 4. The fresh air goes to air filter first and then is pressurized by a turbocharger. It is cooled to required temperature before injection into cylinders. In the cylinders, the air is mixed with diesel fuel and then pressurized to a certain pressure to reach the spontaneous ignition temperature. The hot exhaust gas discharged from the cylinder will be cooled down first and a part of the flue gas enters the turbocharger. The two sections of the turbocharger were also simulated using Compr blocks and the coolers were simulated by HeatX model blocks in Aspen Plus®.

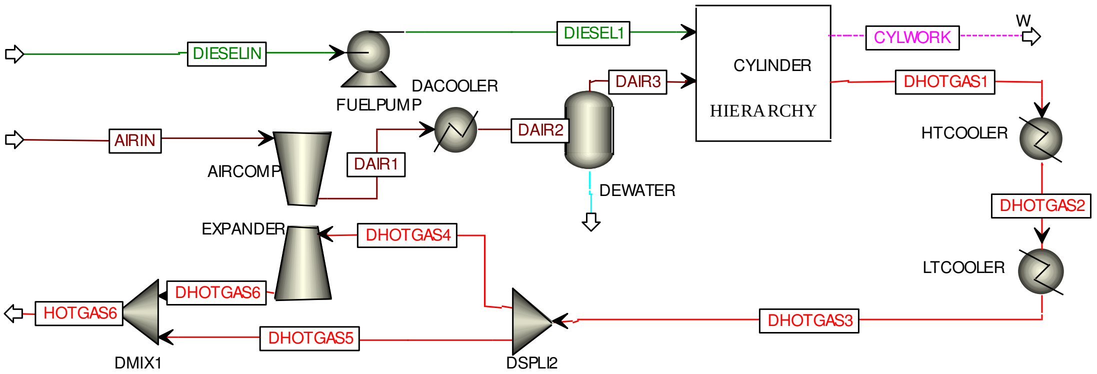


Fig 4. Model flowsheet of the marine diesel engine in Aspen Plus®

### 2.2.3 Model validation of marine diesel engine

For validation purpose of the marine diesel engine model, the simulation results were compared with the performance data at different loads from Wärtsilä product handbook for marine diesel engine [30], as shown in Table 2. The results appear to be in good agreement. The average absolute percentage error (APE) is 2.44% and the maximum absolute percentage error (MAPE) is 7.64% at 75% load.

Table 2: Comparison between model predictions and data from engine handbook

| Load (%) | Fuel consumption (kg/s) | Air flow rate (kg/s) | | Engine output (kW) | Flue gas flow rate (kg/s) |
|---|---|---|---|---|---|
| 100 | 0.537 | 18.8 | Handbook | 10800 | 19.3 |
| | | | Model | 10805 | 19.34 |
| | | | APE(%) | 0.05 | 0.21 |
| 85 | 0.441 | 15.98 | Handbook | 9180 | 17.1 |
| | | | Model | 8905 | 16.4 |
| | | | APE (%) | 3.00 | 4.09 |
| 75 | 0.401 | 14.1 | Handbook | 8100 | 15.7 |
| | | | Model | 8062 | 14.5 |
| | | | APE (%) | 0.47 | 7.64 |
| 50 | 0.27 | 10.3 | Handbook | 5400 | 10.3 |
| | | | Model | 5477 | 10.57 |
| | | | APE (%) | 1.43 | 2.62 |

## 2.3 Modelling of ship energy system

The single train flowsheet of Aspen Plus® model of the ship energy system is presented in Fig. 5. It consists of three main parts including the diesel engine propulsion system, auxiliary power generation and WHR system.

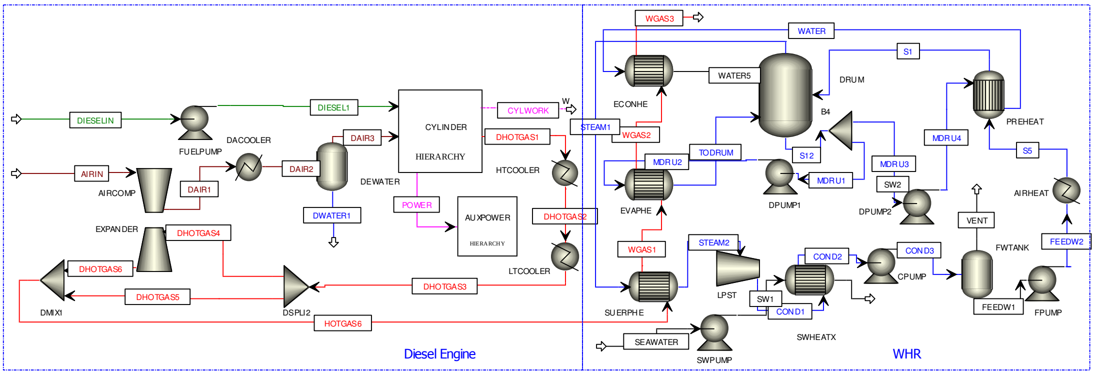


Fig 5. Flowsheet of the ship energy system (single train) in Aspen Plus®

The flue gas discharged from diesel engine goes to the WHR system. Using an integrated heat exchanger to recover heat from the flue gas of diesel engines, the WHR system is to produce superheated steam, which expands in a steam turbine coupled to an electric generator, thus generating electricity. The integrated heat exchanger (see Fig. 2) compromises three parts: the economizer, the evaporator and the superheater. The steam discharged from steam turbine is condensed and then pumped by the feed water pump into the feed water tank. The feed water is initially preheated by air from the high temperature stage of the engine and then enters the water/steam drum.

For the model developed in Aspen Plus®, the STEAMNBS property method is used for steam cycle for accurate evaluation of the steams properties. The three sections of the integrated heat exchanger have been modelled as HeatX blocks. The HeatX model determines the outlet stream conditions based on heat and material balances and estimates the surface area requirement using a constant value as the heat transfer coefficient. The steam turbine is simulated by Compr block. Table 3 presents the process conditions and thermal performance of single train WHR system at 85% load, which is normally the design pitch point with maximum propeller efficiency for marine diesel engine [30]. It is noticed that the total heat energy recovered from flue gas is around 3397.28 $kW_{th}$ and the electricity generated from WHR system is about 662.20 $kW_e$. The energy conversion efficiency is around 19.1% for WHR system.

Table 3. Simulation results of single train WHR system at 85% load

| Items | Value |
|---|---|
| Flue gas flow rate (kg/s) | 16.42 |
| Flue gas inlet temperature (°C) | 362.00 |
| Steam pressure (bar) | 8.50 |
| Feed water tank pressure (bar) | 1.20 |
| Condenser pressure (bar) | 0.065 |
| Minimum pinch temperature (°C) | 10.0 |
| Flue gas exiting temperature (°C) | 170.1 |
| Flow rate of steam generated (kg/h) | 4207.99 |
| Superheater thermal duty ($kW_{th}$) | 344.75 |
| Evaporator thermal duty ($kW_{th}$) | 2446.40 |
| Economiser thermal duty ($kW_{th}$) | 606.13 |
| Steam generator electric power ($kW_e$) | 683.23 |
| Feed water pump power ($kW_e$) | 1.91 |
| Economiser circulation pump power ($kW_e$) | 0.23 |
| Evaporator circulation pump power ($kW_e$) | 0.48 |
| Condensate water pump power ($kW_e$) | 0.30 |
| Condenser sea water pump power ($kW_e$) | 18.13 |
| WHR net electric power ($kW_e$) | 662.20 |

## 3 Model development of carbon capture, compression and storage

### 3.1 Onboard carbon capture

For fossil fuel-fired power plants, carbon capture based on chemical absorption is the most promising approach for large scale commercial deployment [24, 31]. Using amine solvent to absorb $CO_2$ from flue gases is a proven technology [23] although great amount of thermal energy is required for rich solvent regeneration which results in high cost of carbon capture and preventing its commercialization [32, 33]. However, its application for capturing $CO_2$ from ships encounters several challenges because ships are constantly moving vessels with limited space as well as limited supply of utilities [34].

Table 4. Limitations of onboard CCS in a typical marine vessel

| Features of marine vessel | Limitations of onboard CCS |
|---|---|
| Offshore | Tank storage of solvent and captured $CO_2$ |
| Limited space | Sizes of equipment |
| Limited utilities | Supply of heat, electric power and cooling utilities |

| | |
|---|---|
| Constant movement | Construction limitation (such as heights of the columns) |

Table 4 summarized the limitations of onboard CCS considering several features of ships. It is easy to understand that storage tanks are required for both solvent make-up and captured $CO_2$. In CCS onshore application, $CO_2$ will be pressurized to dense phase for pipeline or motorway transport to onshore or offshore geography storage site [35, 36]. But for onboard application, captured $CO_2$ will be stored in liquid phase in tanks, which could be unloaded after ships reach the port. For water supply, Kvamsdal et al. [37] presented water in an solvent-based PCC process at an offshore platform could be in a neutral balance without make-up. In terms of cooling utility, seawater is a good source for cooling down the hot stream to atmosphere temperature. However, it is not suitable for cryogenic process, in which the target operating temperature is lower than -50 °C. Another main limitation is that the equipment size of CCS system should be minimized to occupy less space and less weight. However, there should be a trade-off between equipment size and energy consumption in terms of economic performance perspective.

One special consideration is about the height of the absorber and the stripper, which are two main pieces of equipment of this carbon capture process. The total height of the packing is one of key factors to consider. Higher packing bed benefits the absorption efficiency. Previous studies showed that for CCS onshore applications, the normal range of the packing height of the absorber and the stripper is from 20 to 30.6 meters [33, 38, 39]. Adding the height of the base, the spaces of the bottom and the top of the column and the space between each packing bed for gas-liquid re-distribution, the total height could then be around 50 meters. Even for large size vessels, this packing height is not realistic from ship design point of view.

### 3.2 Development of rate-based model of carbon capture process

Solvent-based carbon capture process uses chemical solvent such as Monoethanolamine (MEA), a benchmark solvent [40], to absorb $CO_2$ in flue gas from fossil fuel-fired power plants or industrial facilities. To describe this reactive absorption process, the rate-based model using Aspen Plus® was proven to be able to provide an acceptable accuracy for performance prediction [41, 42].

The model of PCC capture plant used in this study is developed using Aspen Plus® based on our previous studies [43], to which more details can be referred. Fig. 6 shows the model flowsheet of this PCC process. The packing sections of the absorber and stripper are specified first with the same type of packing and with the same dimensions of the pilot plant. Then the simulation results using this model were compared with the experimental data for validation purpose. The validation results show a good agreement between model predictions and experimental data regarding several key design parameters and operational variables such as lean loading, rich loading, capture level and the temperature profiles of both the absorber and the stripper [43]. In terms of solvent selection, although 30wt% MEA is regarded as a standard solvent historically, 35wt% MEA solvent was presented in more recent publications [44, 45] and also one key report from IEAGHG [31], considering its better balance between solvent regeneration heat requirement, degradation and corrosivity.

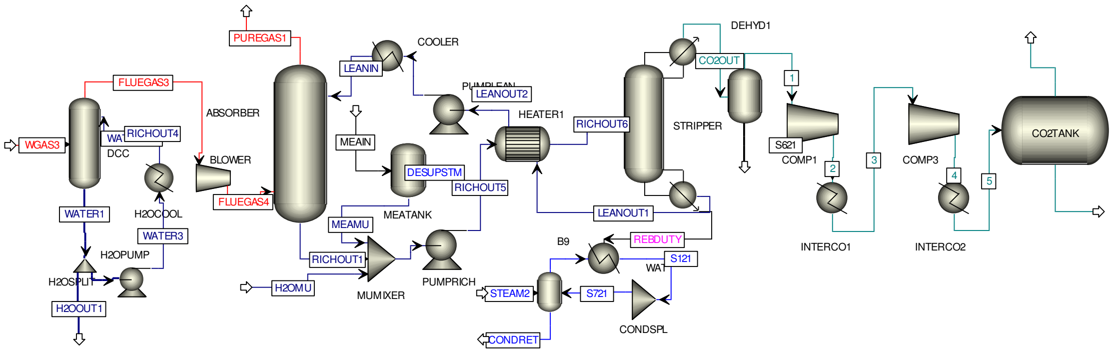


Fig 6. The flowsheet of PCC process with $CO_2$ compression and storage in Aspen Plus®

In order to describe this process better, several technical terms are defined as follows.

$CO_2$ loading in lean solvent (lean loading) and rich solvent (rich loading) in mole basis are defined in Equation (1).

$$CO_2\ loading\ (mol\ CO_2/molMEA) = \frac{[CO_2] + [HCO_3^-] + [CO_3^{2-}] + [MEACOO^-]}{[MEA] + [MEA^+] + [MEACOO^-]} \qquad (1)$$

Specific duty is defined by Equation (3).

$$Q_{spe}\ (GJ/ton\ CO_2) = \frac{Q_{reb}}{F_{CO_2,cap}} \qquad (2)$$

where $Q_{reb}$ is heat duty of the reboiler, $F_{CO_2,cap}$ is mass flow rate of $CO_2$ captured.

### 3.3 Development of models for $CO_2$ compression and tank storage

There are many studies on transporting liquid $CO_2$ via ships. Liquid phase is regarded as the most energy-efficient condition for tank storage [4]. To achieve that, a semi-refrigerated storage tank is preferred at the temperaure around -54 °C per 6 bar to -50 °C per 7 bar [3], which is near the triple point of $CO_2$ (See Fig. 7). For this cryogenic process, great ammount of cooling utility is required. So this semi-refrigerated process is conducted on the onshore sites or the ports for the $CO_2$ ship transporting senarios. However, cooling utility for a cryogenic process (at around -50 °C) is limited on a ship. In this study, the $CO_2$ was liquified by a compression process with much less cooling utility requirement for the intercoolers. According to its phase diagram, the supercritical point of pure $CO_2$ is at the pressure of 73 bar and at temerpature of 31 °C [46] (See Fig. 7). Considering the margin for temperature variation and impact of impurities [47], the pressure of $CO_2$ storage tank was set at the pressure of 100 bar. Therefore, $CO_2$ is in dense phase or supercritical phase for a wide temperature range.

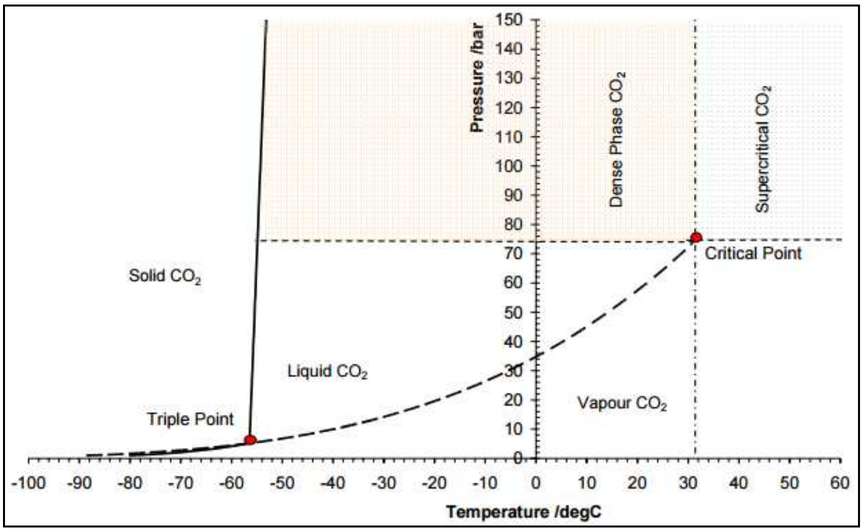


Fig 7. Phase diagram for pure $CO_2$ [48]

As captured $CO_2$ leaves from the stripper top at a pressure of around 2.0 bar, a compression train is required to pressurize the $CO_2$ to its storage pressure. With convetional centrifigual or integrated-gear compressor, 6-16 stages compressor is normally required. The multistage compression not only means a great capital investment for the equipment material, construction and installation cost, but also need a big installation space. Aiming to address the challenge of high investment cost, supersonic shock wave compression technology was developed [49] specific to $CO_2$ compression. This compression technology was successfully tested a 9:1 pressure ratio 8 MW $CO_2$ unit with a 111 bar discharge pressure and its scale-up is in process for 500 - 800MW power plant [50]. The shock wave compressor only needs two stages and the potential capital cost saving for the compression chain is up to 50% [51] in addition to reduced carbon footprint requirement. The discharge temperature of compressed $CO_2$ is as high as 246°C-285°C [52] due to higher pressure ratio of each stage, providing an opportunity for compression heat integration with the main processes of ship energy system and carbon capture plant [32]. In this study, supersonic shock wave compression technology was adopted for $CO_2$ compression. The model parameters of $CO_2$ compression and storage are presented in Table 5.

Table 5. Model parameters of $CO_2$ compression and storage

| Parameters | Value |
|---|---|
| Compressor inlet temperature (°C) | 20.0 |
| Compressor stage number | 2 |
| Compression pressure ratio per stage | 7.2 |
| Compressor isentropic efficiency (%) | 75 |
| Compressor intercoolers exit temperature (°C) | 20 |
| Compressor pressure drop of intercoolers (bar) | 0.05 |
| Pressure of $CO_2$ storage tank (bar) | 100.0 |
| Temperature of $CO_2$ storage tank (°C) | 20.0 |

## 4 Integration of ship energy system with CCS

### 4.1 Scenario set-up

For the ship energy system integrated with CCS, the amount of fuel consumption and the required size of solvent storage tank and captured $CO_2$ storage tanks depend on the distance and the duration of the sailing. To perform case studies using ship energy system integrated with CCS, a typical international sailing is adopted with the route between the ports of Trieste in Italy and Istanbul in Turkey [28] (see in Table 6). During the sailing, it was assumed that the marine diesel engine would be stably operated at 85% load, neglecting the impact of weather condition changes.

Table 6. Key information of the selected sailing route [28]

| Route | Trieste (Italy) and Istanbul (Turkey) |
|---|---|
| Distance (km) | 2,075 |
| Average time per crossing (hour) | 58 |
| Average load of engine | 85% of full power |
| Sailing speed (knot) | 20 |

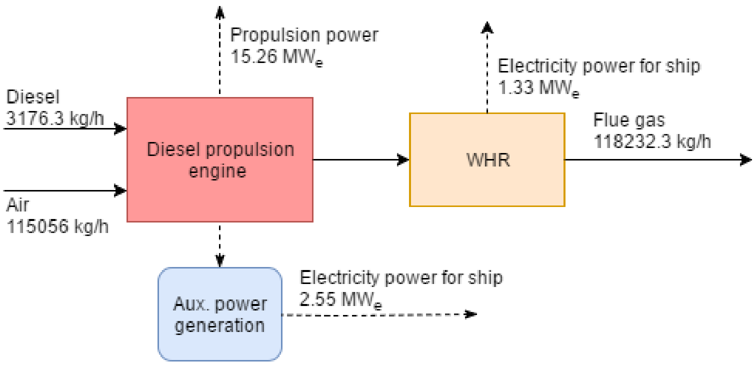
### 4.2 Integration interfaces

When applying CCS for a ship energy system, there are several integration interfaces between these two processes. These include: (1) connecting flue gas from the ship energy system to the PCC process, (2) extracting low pressure steam or other hot process stream from the ship energy system to provide heat for solvent regeneration in the PCC process, (3) returning condensate from the reboiler of carbon capture plant to ship energy system, and 4) supplying electrical power from ship energy system to the PCC and $CO_2$ compression processes.

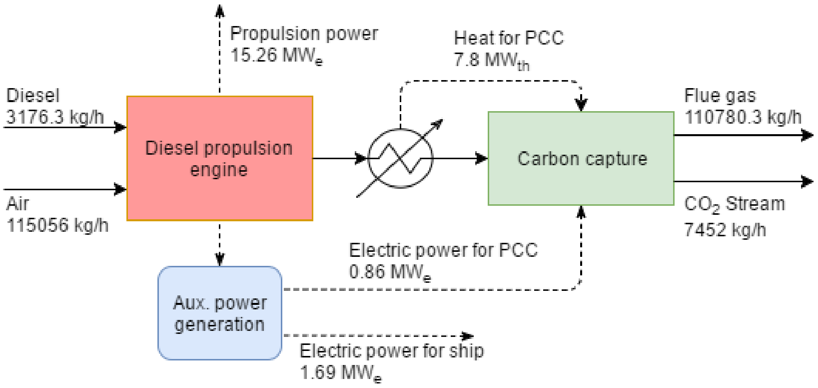
In CCS onshore application such as carbon capture from power plants, the integration of CCS results in a lower power output from power plants. However, in ship CCS scenario, same propulsion power and energy utilities need to be maintained in order to transport goods and/or people for a certain sailing route. Under this constraint, an auxiliary utility source is required because the ship energy system could not provide enough electric power and thermal heat for carbon capture deployment towards 90% carbon capture level. Two design options (i.e. two case studies presented in Sections 4.3 and 4.4) were evaluated in order to compare with the reference cargo ship without carbon capture.

### 4.3 Ship energy system integrated with carbon capture process (Case 1)

Fig. 8 (a) shows the process diagram of the reference cargo ship energy system, which was defined as the Reference Case. Fig. 8 (b) presents the process diagram of the reference cargo ship integrated with carbon capture process, which was defined as the Case 1. As can be seen, Case 1 considers that the energy utility required by carbon capture is supplied by ship energy system itself. Through preliminary thermodynamic analysis, it was found that the heat requirement for solvent regeneration with a capture level of 90% could not be met even using all the steam generated by WHR. In this situation, assuming the WHR system does not exist, the flue gas from the diesel engine was directly lined to the stripper reboiler. After exchanging heat with the solvent, the flue gas then goes to the pre-treatment unit of the CCS system.



(a) Process diagram of the reference cargo ship energy system (Reference Case)



(b) Process diagram of cargo ship energy system integrated with PCC process (Case 1)

Fig 8. Process diagrams of (a) the reference cargo ship energy system (Reference Case) and (b) the cargo ship energy system integrated with carbon capture process (Case 1)

### 4.4 Carbon capture with an additional diesel gas turbine power plant (Case 2)

In Case 2, an additional gas turbine was employed to provide both electricity and thermal heat to the carbon capture plant towards a carbon capture level of 90%, whose process diagram can be seen in Fig. 9. Same with Case 1, no WHR system was used in Case 2. Flue gases from both the marine diesel engine and the additional diesel gas turbine are directly lined to the stripper reboiler. The part of electricity, which is 1.33 MW$_e$ generated from WHR systems in Reference case is provided by the additional diesel gas turbine. There are two considerations: (1) it avoids energy loss during a complex conversion process, such as the WHR system in Reference Case, and (2) it makes the diesel gas turbine power plant in balance between power generation and producing thermal heat to carbon capture plant.

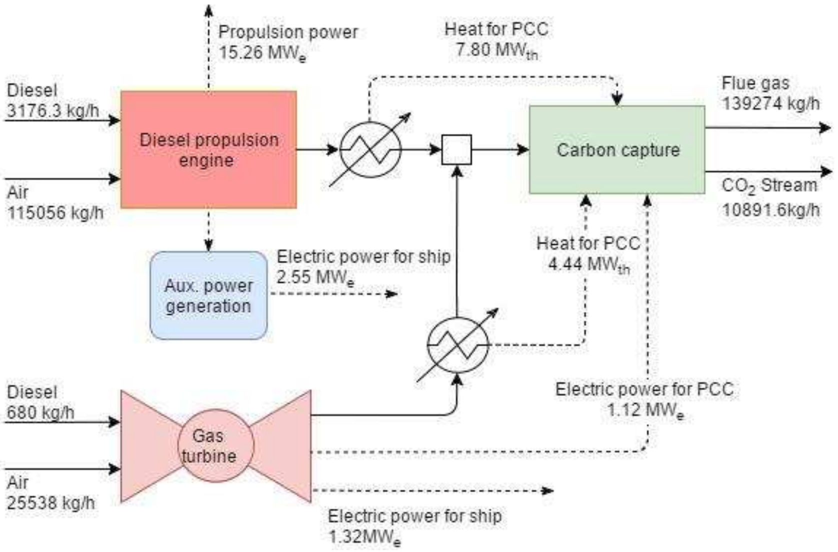


Fig. 9. Process diagrams of ship energy system integrated with carbon capture process with an additional diesel gas turbine power plant (Case 2)

The type of gas turbine used in this process is an industrial multi-fuel gas turbine [53, 54] with a maximum electricity output of 3.5 $MW_e$. Diesel was selected as the fuel to avoid an additional storage and supply system for other types of fuels different from the propulsion engine fuel. The modelling of gas turbine in Aspen Plus® was performed by combining three process sections including air compressor, combustion reactor and gas turbine. The model flowsheet can be seen in Fig. 10. The combustor section was simulated with an RGibbs reactor block [55]. The vent oxygen is controlled to a certain value to ensure complete (equilibrium) combustion. It calculates the equilibriums by the Gibbs free energy minimization, thus the complicated calculations of reaction stoichiometry and kinetics are avoided with only required inputs of the temperature and the pressure of the reactor. PR-BM was used for the property calculations for this gas turbine. The key process parameters were presented in Table 7.

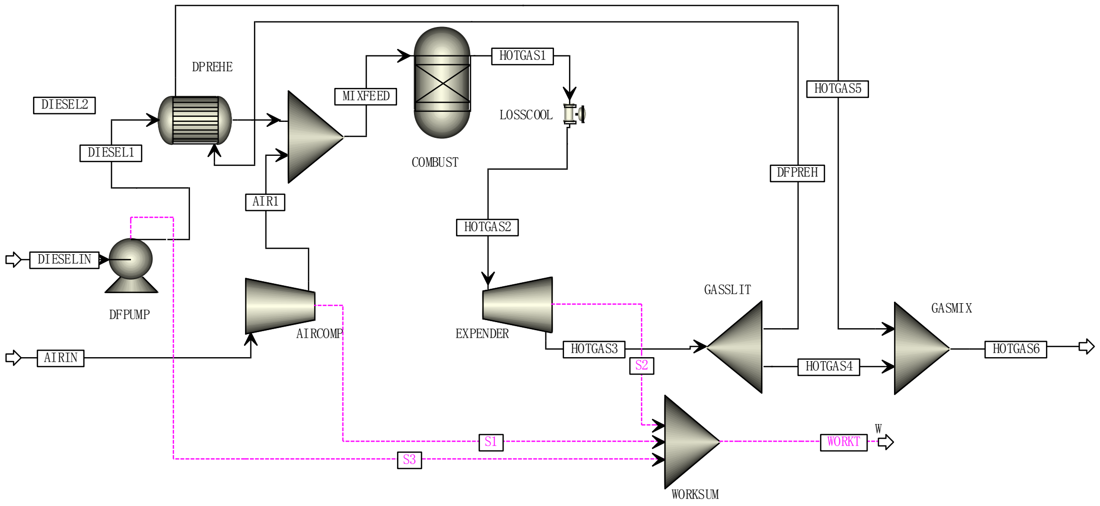


Fig. 10. Model flowsheet of diesel gas turbine in Aspen Plus®

Table 7. Process parameters of diesel gas turbine

| Process conditions | |
|---|---|
| Ambient temperature (°C) | 20 |
| Atmospheric pressure (bar) | 1.00 |
| Diesel fuel flow rate (kg/h) | 680 |
| Air mass flow rate (kg/h) | 25,538 |
| Compressor pressure ratio | 9.7 |
| Combustor temperature (°C) | 1,227.2 |
| Compressor isentropic efficiency | 0.84 |
| Turbine isentropic efficiency | 0.89 |
| Turbine back pressure (bar) | 1.03 |
| Exhaust gas temperature (°C) | 686.3 |
| Electricity generated ($kW_e$) | 2442 |

## 5 Results and discussions

### 5.1 Thermal performance of the integrated systems

Table 8 summarized the thermal performance of these three cases. In the Reference Case, the electric power generated by WHR is 1.32 $MW_e$, which could be a significant supplement to the ship electric power network. The overall energy efficiency is around 51.19% based on low heat value (LHV). In Case 1, the carbon capture level can reach 73% with same fuel consumption. However, it should be noticed that, because the original WHR system was cancelled and auxiliary power is required for carbon capture and compression, the shortage of electric power could be around 2.18 $MW_e$ compared with Reference Case, which may not be acceptable. The overall energy efficiency of Case 1 is 45.35%. In Case 2, with 21.41% more diesel fuel consumption, the auxiliary diesel power plant provides 2.44 $MW_e$ electric power and 4.43 $MW_{th}$ heat to the system, which could make the carbon capture level to reach 90%. The overall energy efficiency is around 42.16% in LHV.

Table 8. Thermal performance of the ship energy system with\without CCS system

| Description | Reference Case (no CCS) | Case 1 (with CCS, but without additional utilities supply) | Case 2 (with CCS and additional utilities supply) |
|---|---|---|---|
| Diesel consumption of propulsion engines (kg/h) | 3176.28 | 3176.28 | 3856.28 |
| Propulsion power output (MW) | 15.26 | 15.26 | 15.26 |
| Ship aux. electric power generation ($MW_e$) | 2.55 | 1.69 | 2.55 |
| WHR electric power output ($MW_e$) | 1.32 | - | - |
| Electric power output of the additional diesel gas turbine ($MW_e$) | - | - | 2.44 |

| | | | |
|---|---|---|---|
| Electric power consumption of auxiliary in capture process ($MW_e$) | – | 0.10 | 0.11 |
| Electric power consumption of $CO_2$ compression ($MW_e$) | – | 0.76 | 1.01 |
| Stripper reboiler duty ($MW_{th}$) | – | 7.80 | 12.21 |
| Fuel consumption per single trip (tons) | 184.22 | 184.22 | 223.67 |
| $CO_2$ emission per single trip (tons) | 593.10 | 172.00 | 59.31 |
| Capture level (%) | – | 73.00 | 90 |
| Overall energy efficiency (%, fuel LHV) | 51.19 | 45.35 | 42.16 |

### 5.2 Process conditions and equipment sizes of carbon capture process

To match the capacity requirement (i.e. to handle the flue gas from the ship energy system), the model of $CO_2$ capture process developed and validated at pilot scale has been scaled up based on chemical engineering principles to estimate packed column diameters and pressure drop [56]. The details of the scale-up method can refer to previous studies by Lawal et al. [57] and Luo [43].

The process parameters and equipment sizes of the capture plant in Cases 1 and 2 are presented in Table 9. In both cases, the packing heights of the absorber and the stripper are 12.5m and 6.5m respectively, much shorter than onshore CCS scenario. However, low packing height may lead to a high L/G ratio. Slightly higher rich loading in Case 1 results in a smaller L/G ratio and lower specific duty compared with Case 2. The capture level reaches 90% in Case 2, which causes significant equipment size increments, saying 36.1% and 72.3% increment of the cross-section area for the absorber and stripper respectively. The reason for the difference is that the required cross-section area of a column is decided by both gas phase and liquid phase loadings inside the column. The flow rate of flue gas feed increases by 22.20% in Case 2 because of extra diesel consumption for the auxiliary power plant. However, the captured $CO_2$ increases 53.14%, which results in a bigger stripper. It is also found that the volume of $CO_2$ storage tank is big. But this tank could be unloaded and replaced with empty one in the intermedium ports in the sailing route [58], then the volume requirement could decrease by a big margin.

Table 9. Overall performance of the carbon capture process

| Description | | Case 1 | Case 2 |
|---|---|---|---|
| Process conditions | Flue gas flow rate (kg/s) | 32.84 | 40.13 |
| | Flue gas $CO_2$ content (mol %) | 5.69 | 5.66 |
| | Solvent MEA content (wt%) | 35.00 | 35.00 |
| | Capture level (%) | 73.00 | 90.00 |
| | $CO_2$ captured (kg/s) | 2.07 | 3.17 |
| | L/G ratio (kg/kg) | 1.73 | 2.06 |
| | Lean loading (mol $CO_2$/ mol MEA) | 0.308 | 0.308 |
| | Rich loading (mol $CO_2$/ mol MEA) | 0.481 | 0.457 |
| | Stripper reboiler duty ($MW_{th}$) | 7.80 | 12.21 |

| | | | |
|---|---|---|---|
| | Specific duty ($GJ_{th}$/ton $CO_2$) | 3.77 | 3.85 |
| Equipment sizes | Absorber diameter (m) | 4.2 | 4.9 |
| | Absorber packing type | Mellapak 250Y | Mellapak 250Y |
| | Absorber packing height (m) | 12.5 | 12.5 |
| | Absorber flooding factor | 0.651 | 0.639 |
| | Stripper diameter (m) | 1.6 | 2.1 |
| | Stripper packing type | Mellapak 250Y | Mellapak 250Y |
| | Stripper packing height (m) | 6.5 | 6.5 |
| | Stripper flooding factor | 0.639 | 0.618 |
| | MEA tank volume ($m^3$) | 0.65 | 1.02 |
| | $CO_2$ tank volume ($m^3$) | 561.30 | 937.4 |

# 6 Economic Evaluation

## 6.1 Economic index

For the economic evaluation, the cost of $CO_2$ avoided (CCA) was used as the economic index in this study. CCA was calculated through dividing total annual cost (TAC) by $CO_2$ captured annually, as expressed in Equation (3). TAC is a sum of annualized capital expenditure (ACAPAX), fixed operational expenditure (FOPEX) and variable operational expenditure (VOPEX) as defined in Equations (4) and (5).

$$CCA = \frac{TAC}{F_{co_2,cap}} \tag{3}$$

$$TAC = ACAPEX + FOPEX + VOPEX \tag{4}$$

$$ACAPEX = CAPEX \times CRF \tag{5}$$

The following assumptions were made: (1) all the costs are corrected to €2016 using the harmonised index of consumer price (HICP) in European zone [59], (2) the captured $CO_2$ mixture has no economic value, (3) MEA-solvent make-up rate is around 1.5 kg per ton of $CO_2$ captured [60], (4) the major cooling utility is provided from sea water [28].

## 6.2 Cost breakdown

### 6.2.1 CAPEX

CAPEX includes equipment itself, materials and installation, labour cost, engineering and management cost and other costs happened during the project construction and commissioning. As the basis for the equipment cost estimation , the type and material selection of main equipment can refer to two IEAGHG reports [31, 61].

The direct material cost could be calculated based on their reference value in each case and the specific scaling factor for different types of equipment, by Equation (6) [62].

$$PC = PC^{o}\left(\frac{X}{X^{o}}\right)^{m}\left(\frac{I}{I^{o}}\right) \quad (6)$$

where $X$ is the value of selected index related to equipment capacity, $I$ is cost index for different years and geographical areas, $m$ is the specific scaling factor and the value is 1.0 for structured packing inside the columns and 0.6 for other equipment according to six-tenths rule [63]. $PC^{o}$ is the direct material cost of the base case, which can be derived from the IEAGHG report [31].

The annualized CAPEX is the total CAPEX multiplying by capital recovery factor (CRF), which is calculated by Equation (7) [62].

$$CRF = \frac{i(i+1)^{n}}{(i+1)^{n}-1} \quad (7)$$

where $n$ is the economic life of plant and $i$ is the interest rate. It is assumed a project life of 25 years and 8% of interest rate.

### 6.2.2 Fixed OPEX

Fixed OPEX (FOPEX) includes long term service agreement costs, overhead cost, operating and maintenance cost (O&M) and other costs fixed for the plant no matter if it is running at partial or full load or shutdown. FOPEX can be simply calculated by Equation (8)

$$FOPEX = 0.03 \times CAPEX \quad (8)$$

### 6.2.3 Variable OPEX

VOPEX includes the cost of electricity consumption for pumps/blower/compressor, the cost of heat for solvent regeneration, the cost of cooling utilities and the cost of MEA solvent make-up. In this study, electric power and thermal heat required by the carbon capture process were supplied by the ship energy system and the auxiliary power plant. The cost of this part can be calculated based on extra fuel consumption. Other utility cost can be calculated by multiplying the market unit price with its amount obtained from the simulation results. The unit prices can be seen in Table 10 with the costs given in Euro.

Table 10. Key economic evaluation cost inputs

| Description | Unit | Value | Source |
|---|---|---|---|
| Diesel fuel price | €//L | 1.391 (in Italy) | DKV [64] |
| MEA price* | €/ton | 1,250 | ICIS [65] |
| Number of roundtrips | /year | 55 | Livanos et al. [28] |
| Ship life | year | 25 | |
| Interest rate | /year | 0.08 | |

* Price of free delivery

### 6.3 Results and discussions

The economic assessment was carried out based on 55 roundtrips per year for this cargo ship. Table 11 summarized the overall cost of $CO_2$ captured and breakdown details. For Case 1, the CCA is around 77.50 €/ton $CO_2$. However, there would be a shortage of 2.18 $MW_e$ for the electric power and the capture level is only around 73%. In Case 2, the major cost is caused by diesel fuel consumption, which accounts for about 61.75% of total annual cost. The CAPEX in Case 2 is obviously higher than in Case 1 because of larger equipment size for the CCS system required and it has an extra diesel gas turbine. With these two main contributors, the CCA in Case 2 is as high as 163.07 €/ton $CO_2$.

Table 11. Economic evaluation results

| Description | | Case 1 | Case 2 |
|---|---|---|---|
| $CO_2$ captured (ton/year) | | 46,321 | 71,627 |
| CAPEX (M€) | | 34.99 | 43.06 |
| Annualized CAPEX (M€/year) | | 2.45 | 3.01 |
| Fixed OPEX (M€/year) | | 1.05 | 1.29 |
| Variable OPEX | Fuel cost (M€/year) | - | 7.25 |
| | Solvent make-up cost (M€/year) | 0.09 | 0.13 |
| Total annual cost (M€/year) | | 3.59 | 11.68 |
| CCA (€/ton $CO_2$) | | 77.50 | 163.07 |

It should be noticed that the cost of $CO_2$ avoidance in Case 2 should be close to the upper limit towards 90% carbon capture level. One reasoning is that the extra fuel consumption not only covers the heat and electricity utilities for CCS system but also fully replenish the electricity generated by original WHR. However, for the newly designed ship energy systems, there could be a large potential to minimize this extra fuel consumption by optimal design considering the balance of different types of utilities. Another reason is that the cost of $CO_2$ storage tank could be reduced by unloading and reloading with empty tanks in intermedium ports but it varies for each sailing route.

Furthermore, the benchmark solvent MEA is used for carbon capture process in this study. With proprietary solvents such as KS-1, the cost of $CO_2$ avoidance could be reduced around 10% [31]. Another cost reduction potential is related with applying process intensification concept, such as rotating packing bed (RPB). With RPB technology, the size of absorber and the stripper could be reduced more than 10 times, which will decrease the capital cost significantly [66].

## 7 Conclusions

This study presented the study on applying solvent-based carbon capture for ships to reduce the $CO_2$ emission from ship energy system through model-based techno-economic assessment. The study discussed the design considerations of on-board CCS against the features of ships, such as offshore, limited space, limited utilities and constant movement. Special attention was put on the packing heights of the columns from ship design point of view. Captured $CO_2$ was pressurized by a compression process to its dense phase or supercritical phase for the temporary tank storage to avoid large amount of cooling utility.

For the model development of the ship energy system, the study first addressed the challenges of modelling single engine cylinder reciprocation process. The models of marine diesel engine and ship energy system were then developed in Aspen Plus® and diesel engine model was validated with data from the product handbook at different engine loads. The validation results appear in a good agreement.

Three cases were analysed for ship energy system with or without the carbon capture system based on an international sailing scenario. In the Reference Case (cargo ship without carbon capture), the electricity generated from WHR is around 1.32 $MW_e$ and the energy efficiency of ship energy system is around 51.15%. In Case 1 (cargo ship with carbon capture, but without additional utilities supply), the heat recovered from flue gas could only meet solvent regeneration heat requirement at 73 % carbon capture level whilst the shortage of electricity is 2.18 $MW_e$ compared with Reference Case. The energy efficiency of ship energy system drops to 45.35%. The cost of $CO_2$ captured is around 77.50 €/ton $CO_2$. In Case 2 (cargo ship with carbon capture), an additional diesel gas turbine was employed to provide 2.44 $MW_e$ electricity and 4.43 $MW_{th}$ heat to the integrated system to achieve carbon capture level to reach 90%, with 21.41% more diesel fuel consumption. The overall energy efficiency drops to 42.16% and the cost of $CO_2$ captured is around 163.07 €/ton $CO_2$. With the potential application for proprietary solvents, process intensification and the new process configuration for the carbon capture process, the cost of $CO_2$ avoidance could reduce.

In a summary, as the first systemic study on applying solvent-based carbon capture for ships, this paper obtained key insights for the integration of ship energy system with carbon capture process, and also provided a solution to capture 90% $CO_2$ emission from ship energy systems, to significantly reduce carbon footprint of cargo ships.

## Acknowledgement

The authors would like to acknowledge the financial support from EU FP7 Marie Curie International Research Staff Exchange Scheme (Ref: PIRSES-GA-2013-612230).

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