Optimization of engine systems with OCC for a new-build LNG carrier

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Executive summary

The EverLoNG project focuses on advancing carbon capture technology for LNG vessels. One of the case studies in the project is a new-build LNG carrier. This report discusses the analysis performed on historical operational data of a similar LNG carrier chartered by TotalEnergies, which is used as input for the new-build vessel. The most optimal engine configuration of this new-build vessel in combination with an on-board carbon capture is determined.

The optimal size for the capture system is determined at processing 8 ton CO_2/h in the flue gas entering the capture system. At this size, the capture system can avoid 75.7% of the on-board emissions, at a fuel penalty of 10.7% compared to the base case. In this case, 73.7% of the heat required for the capture system is recovered from the exhaust. Both the remaining heat demand of the capture system and the electricity demand of the capture and liquefaction system contribute equally to the resulting fuel penalty.

TotalEnergies has provided 575 days of historical operational data for one of their chartered LNG carriers. Engine performance data is acquired for several engine types to allow comparison of these engines when considering an on-board carbon capture system. A novel methodology is introduced in this study which allows the calculation of the performance of a carbon capture system in relation to the different engines considered, by calculating the performance at each datapoint in time (hourly data was used in this study). Following this methodology, a digital cousin of the energy system of vessels can be generated, which can aid in determining optimal configurations for an engine system in combination with an on-board carbon capture process.

Different cases were evaluated to assess the influence of several parameters on the efficiency of the vessel with on-board carbon capture. For the reference engine in this study, the heat load of the vessel, the NOx tier of the engine, the type of capture solvent and the waste heat recovery unit outlet temperature were varied. Next to this, four MAN 2-stroke engines and one MAN 4-stroke engine were compared against each other. The main conclusion from this analysis is that the MAN 2-stroke engine equipped with a low-pressure SCR system showed the lowest fuel penalty when considered with an on-board carbon capture system. Even though the engine efficiency of the MAN 2-stroke low pressure SCR system is lower than other engines, the higher exhaust gas temperature allows for more heat recovery for the capture system, giving an overall higher performance. This engine + aftertreatment configuration is selected for the remainder of the study.

More detailed calculations have been performed for the final case, implementing lessons learned from the initial comparison exercise. For example, the electricity demand of the capture system is included in the analysis to generate a system as close to reality as possible.

The results of this study are transferred to the concept design, TEA and LCA exercises in the EverLoNG project, where the system is further detailed.

Table of Contents

1 Introduction 3

2 Case definition and engine/vessel correlations used 4

2.1 Definition of case 4

2.2 Overview of engines evaluated 4

2.3 Engine data used in the study 4

2.4 Design philosophy for the waste heat recovery unit 8

2.5 Heat recovery potential per engine 8

2.6 Base heat load of the vessel 11

2.7 Methane slip correlations 12

3 Data acquisition and methodology for analysing data 13

3.1 Overview of cases studied 14

4 Results of the analysis 15

4.1 Detailed results for the base case (case 3) 15

4.2 Results of comparing different cases 20

4.2.1 Effect of base heat load of the vessel (case 1-5) 20

4.2.2 Effect of WHRU exit temperature (cases 3 and 6) 21

4.2.3 Potential effect of advanced capture solvent (cases 3 and 7) 22

4.2.4 Effect of NOx tier 2 and 3 (cases 3 and 8) 23

4.2.5 Effect of main engine type - 2-stroke comparison (Cases 3, 8, 9, 10, 11, 12) 24

4.2.6 Effect of main engine type (2-stroke versus 4-stroke) 26

4.2.7 Conclusions from comparison study 28

5 Re-analysis of optimal case and results 28

6 Conclusions and recommendations 35

7 References 36

1 Introduction

EverLoNG is a research project focused on advancing carbon capture technology for maritime applications. Recognising the urgent need to decarbonise the shipping industry, EverLoNG has brought together leading industrial and research partners from across Europe to develop, demonstrate, and optimise onboard carbon capture solutions for LNG-fuelled vessels. The project addresses not only the technical challenges of capturing CO_2 emissions at sea, but also the economic and operational aspects of implementing these systems. Through detailed case studies, system integration, and techno-economic assessments, the EverLoNG project assesses the potential for large-scale adoption of carbon capture technology on LNG vessels.

As part of the EverLoNG project, a full-scale case study for a 174,000 m^3 LNG carrier, chartered by TotalEnergies is worked out. This report discusses part of that work and focuses on the analysis of the operational data received from the chartered vessel and discusses a holistic approach for optimization of the vessel's energy system when applying on-board carbon capture. The results as published in this report were further used in the EverLoNG project to perform a full TEA exercise. A preliminary iteration of the work described in this report has been previously presented at the GHGT-17 conference [1].

2 Case definition and engine/vessel correlations used

2.1 Definition of case

An LNG carrier chartered by TotalEnergies and with historical operational data available is considered as the basis for this study. This vessel contains two main propulsion engines (12590 kW at 100% MCR) and 4 auxiliary engines. There are two larger and two smaller auxiliary engines. To understand the impact of the main engine type and configuration on CO_2 emissions reduction via onboard CO_2 capture, different main engine types are considered in this study, but the same auxiliary engines are considered for each case, except for the diesel electric system. In diesel electric systems, the engine drives an electric generator, which in turn drives the propellor and other electricity users on-board. For the diesel electric case, the power demand of the main and auxiliary engines is combined in the analysis, as normally the power for the complete vessel is delivered from those engines.

2.2 Overview of engines evaluated

There are five different engines analysed in this study:

- 2-stroke MAN 5G70ME-C10.5-GI-EGRBP (Tier 2 NOx)
- 2-stroke MAN 5G70ME-C10.5-GI-EGRBP (Tier 3 NOx)
- 2-stroke MAN 5G70ME-C10.5-GI-LPSCR (Tier 3 NOx)
- 2-stroke MAN 6G70ME-C10.5-GA-EGRBP (Tier 3 NOx)*
- 4-stroke MAN 49/60DF in a dual fuel diesel electric setup (Tier 3 NOx)

*The ME-GA engine type has been discontinued by MAN, as announced near the end of the EverLoNG project [2].

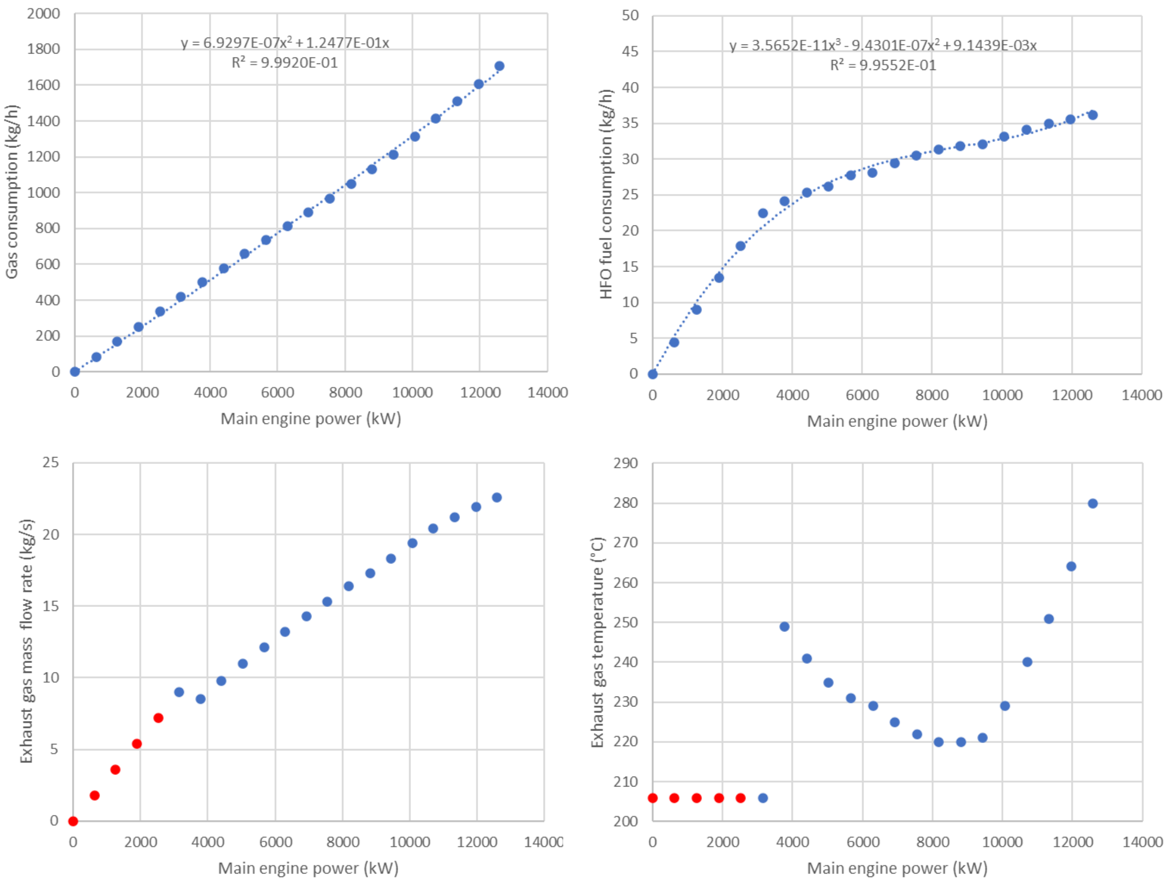
The 5G70ME-C10.5-GI-EGRBP is the base case engine used in this study, as this is the actual engine installed on the LNG carrier considered. For this engine, Tier 2 and Tier 3 NOx configurations are evaluated to assess the effect of these configurations on the performance of a carbon capture system. For all other engines, only Tier 3 is considered, as high NOx concentrations seem to greatly affect the solvent degradation rates as demonstrated in EverLoNG [3]. The MAN 5G70ME-C10.5-GI-LPSCR is evaluated in this study, as it represents a case where the exhaust gas temperatures are higher because of the addition of a low-pressure SCR system. While the fuel efficiency is worse than the base case engine, higher exhaust gas temperatures could potentially mitigate this negative effect, as more heat can be recovered for the carbon capture system. The MAN 6G70ME-C10.5-GA-EGRBP engine is a gas admission (GA) engine and is added to the study since it represents the alternative to a gas injection (GI) engine. Other than this, the 5G70ME-C10.5-GI-LPSCR and the 6G70ME-C10.5-GA-EGRBP engines are very similar. The final engine is the 4-stroke MAN 49/60DF. 4-stroke diesel electric engines have quite different operational parameters, and often have much higher exhaust gas temperatures, which could be beneficial when a ship is equipped with a carbon capture system.

2.3 Engine data used in the study

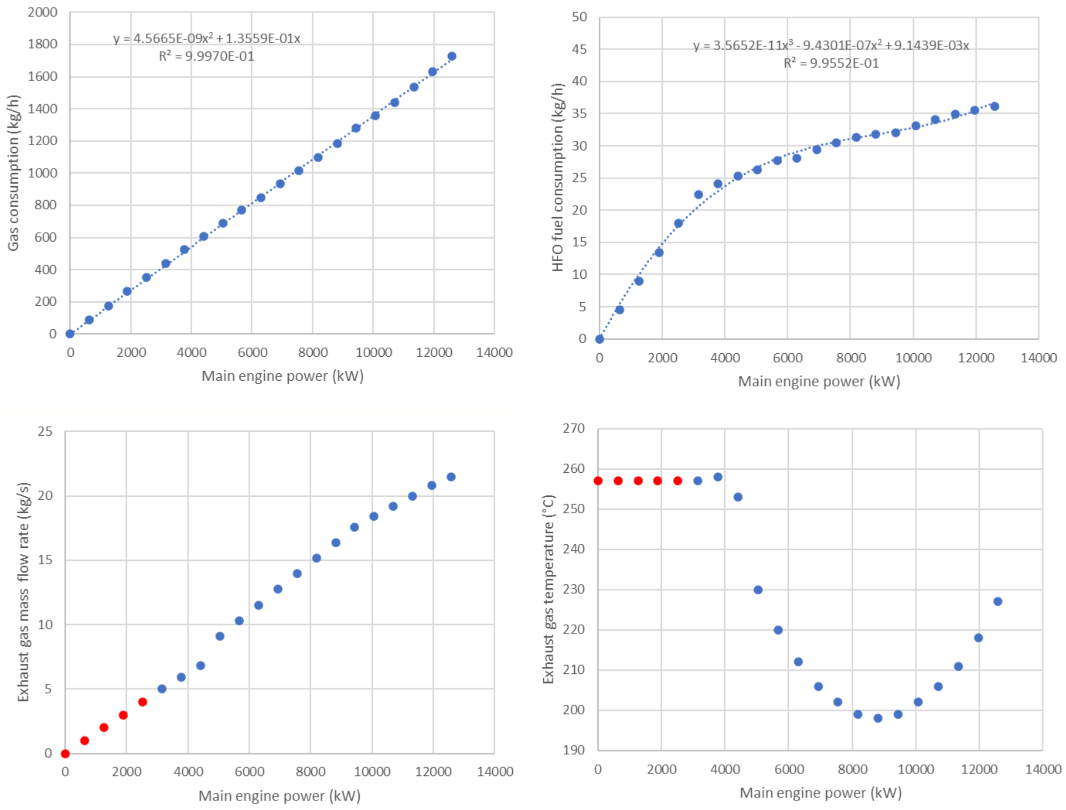
Shop test data is obtained for every engine. For the MAN 2-stroke engines, the data is extracted from the public CEAS system [4]. The 4-stroke diesel electric engine data is obtained from MAN-ES. Data from a technical file supplied by Total Energies is used for the auxiliary engines.

For every engine type considered in the study, correlations are generated for the gas flow rate, pilot fuel flow rate, exhaust gas flow rate and exhaust gas temperature as a function of engine power. These correlations are shown in Figure 1. Blue dots are data retrieved from the engine files, while red dots represent missing data which is estimated based on extrapolation of the data.

2-stroke MAN 5G70ME-C10.5-GI-EGRBP (Tier 2 NOx)



2-stroke MAN 5G70ME-C10.5-GI-EGRBP (Tier 3 NOx)



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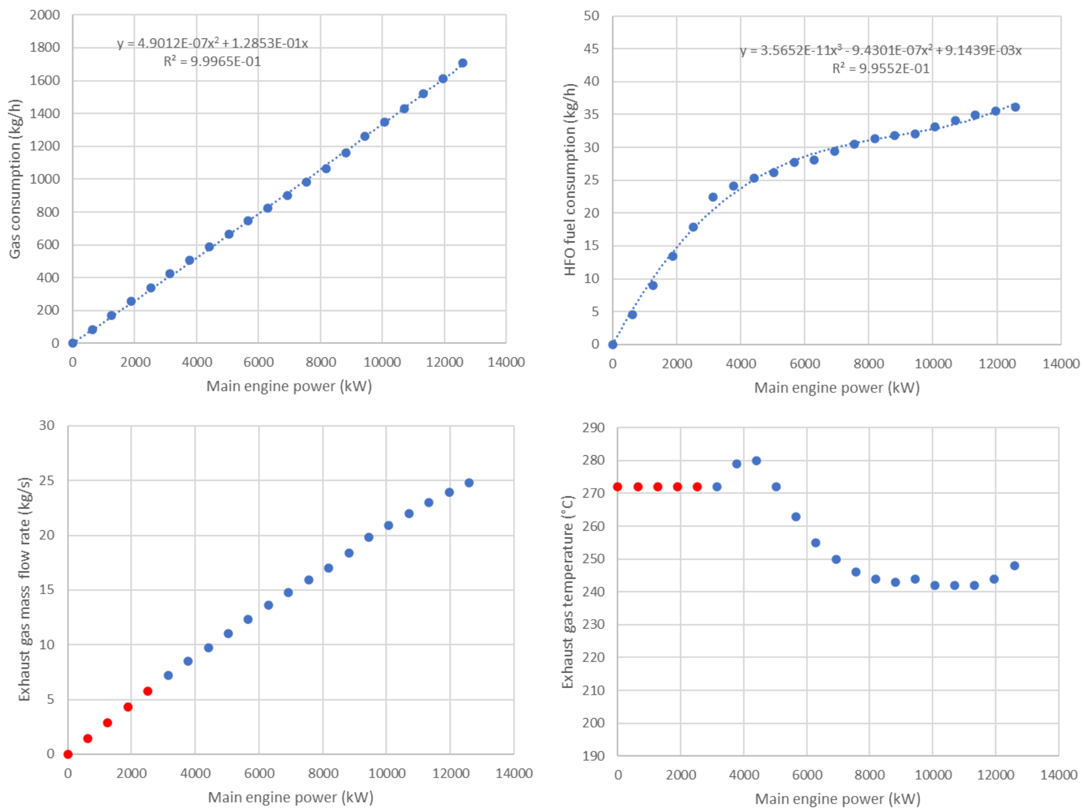
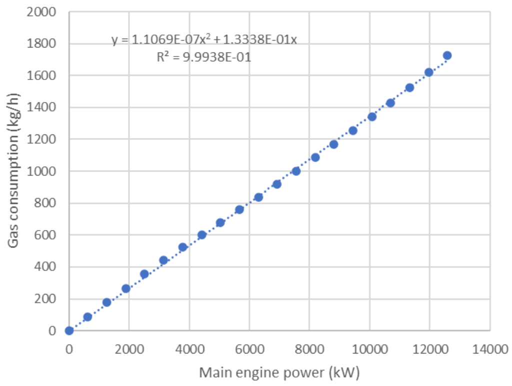
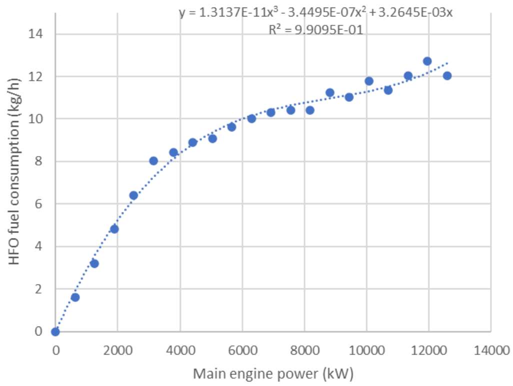
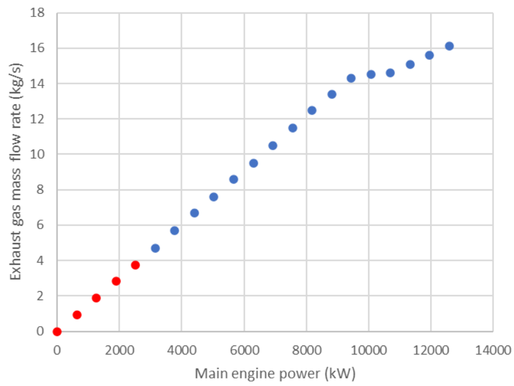
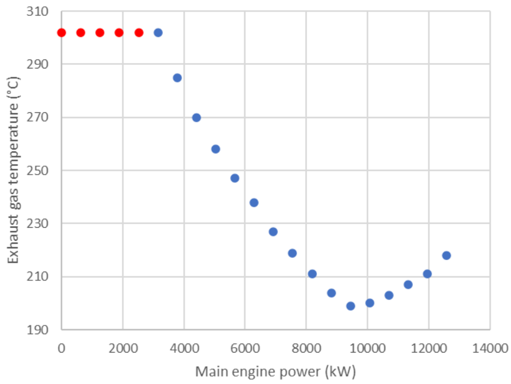


2-stroke MAN 6G70ME-C10.5-GA-EGRBP (Tier 3 NOx)

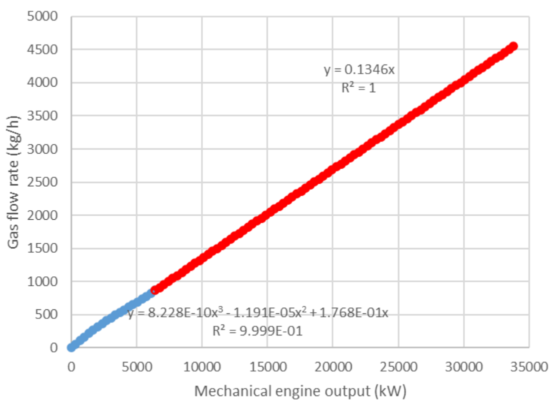


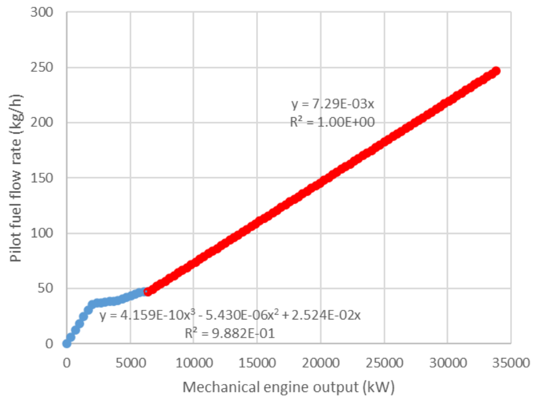


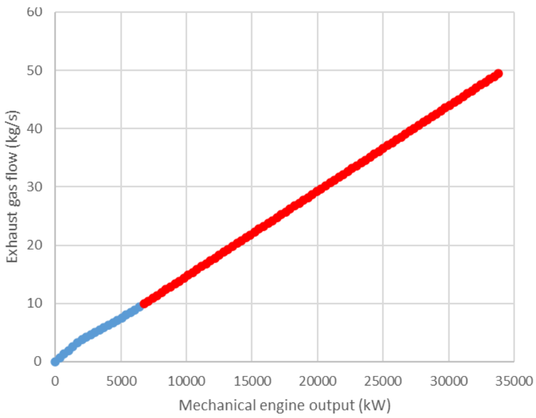


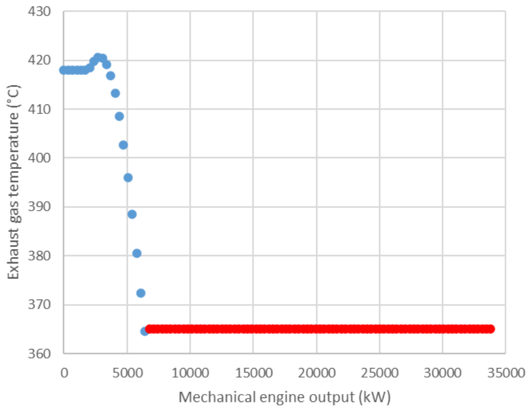


4-stroke MAN 49/60DF (Tier 3 NOx)









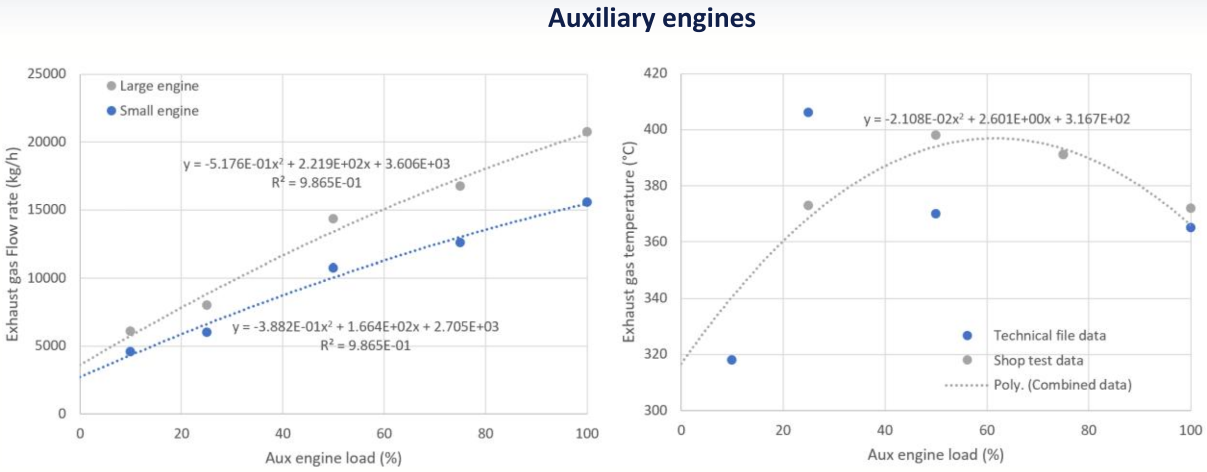


Figure 1, gas fuel flow rate, pilot fuel flow rate, exhaust gas flow rate and exhaust gas temperature correlations for all engines used in this study.

2.4 Design philosophy for the waste heat recovery unit

The exhaust gas mass flow rates and the exhaust gas temperatures are used to calculate the amount of heat that can be produced from the exhaust gas. This is calculated for each engine load using *Equation 1*, in which Q_{prod} is the potential heat recovery from the exhaust gas (kW_{th}), $m_{exhaust}$ is the mass flow rate of the exhaust gas (kg/s), $Cp_{exhaust}$ is the average exhaust gas heat capacity (kJ/kg-°C) and ΔT_{WHRU} is the temperature difference of the exhaust gas in the waste heat recovery unit (WHRU). For simplicity, the heat capacity of the exhaust gas is assumed to be constant for this study (1.075 kJ/kg-°C), but it must be noted that the heat capacity is a function of exhaust gas temperature and composition. The outlet temperature of the WHRU is assumed 135 °C unless stated otherwise. While 180 °C is the standard in the marine industry, this is mainly dictated by sulphuric acid condensation, which in principle is not a problem for LNG fuelled systems, as sulphur concentrations are very low in general. 135 °C is chosen as this temperature leads to a reasonable temperature difference to a standard stripper temperature of a carbon capture system (120 °C). For the exhaust gas temperature and mass flow rate, there are no correlations available below 25% MCR for most engines. The gas flow rate is assumed to linearly decrease to 0 at 0% MCR. The exhaust gas temperature is assumed to be constant below 25% MCR, as shown in Figure 1. The same calculations are also performed for the auxiliary engines. The auxiliary engines are not changed when considering different engines. They remain constant throughout this work, except for the calculations on the 4-stroke system.

$$Q_{prod} = m_{exhaust} \cdot Cp_{exhaust} \cdot \Delta T_{WHRU} \qquad \text{Equation 1}$$

2.5 Heat recovery potential per engine

The resulting correlations for the potential heat recovery from the exhaust gases can be found in Figure 2 for the auxiliary engines and in Figure 3 for the main engines. The highest heat recovery potential is found for the 4-stroke Diesel electric system. The exhaust gas temperatures are higher for this engine than the other engines evaluated in this study, but it must be noted that the heat recovery potential is evaluated for the complete ship (2 main engines and several auxiliary engines) and not per main engine (note the different x-axis in Figure 1 compared to the other engines). Also, the correlation is assumed linear (indicated with the red dots) beyond a certain load for the diesel electric system: in reality, in a multiple-engine diesel electric setup, there will be discontinuities in the correlations, corresponding with the loads at which additional engines are switched on or off. Including these discontinuities in the correlations is not straightforward, as the operational data in this study is based on the operation of a 2-stroke engine. Instead, the choice is made to assume conservative, linear correlations for the diesel electric system, making the results more robust and broadly applicable. Regarding the 2-stroke engines, the highest heat recovery potential is for the GI-EGRPB Tier 2 engine and the GI-LPSCR engine. This is followed by the GI-EGRBP (Tier 3). The GA-EGRPB engine has the lowest heat recovery potential of all engines considered in this study.

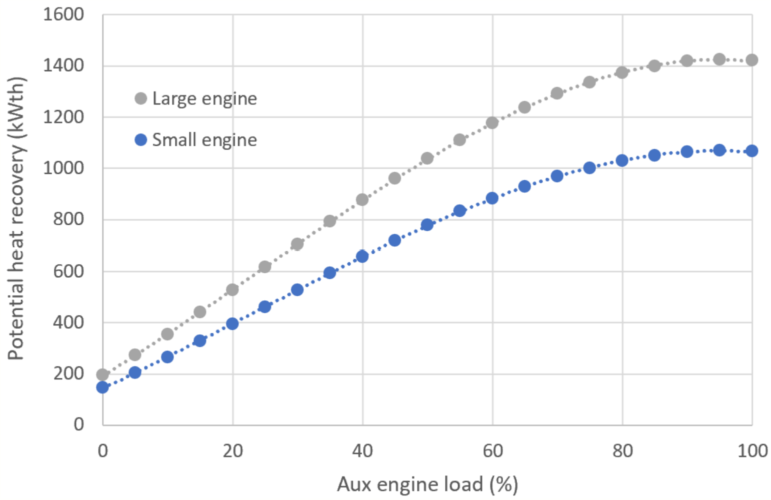


Figure 2, heat recovery potential for the auxiliary engines.

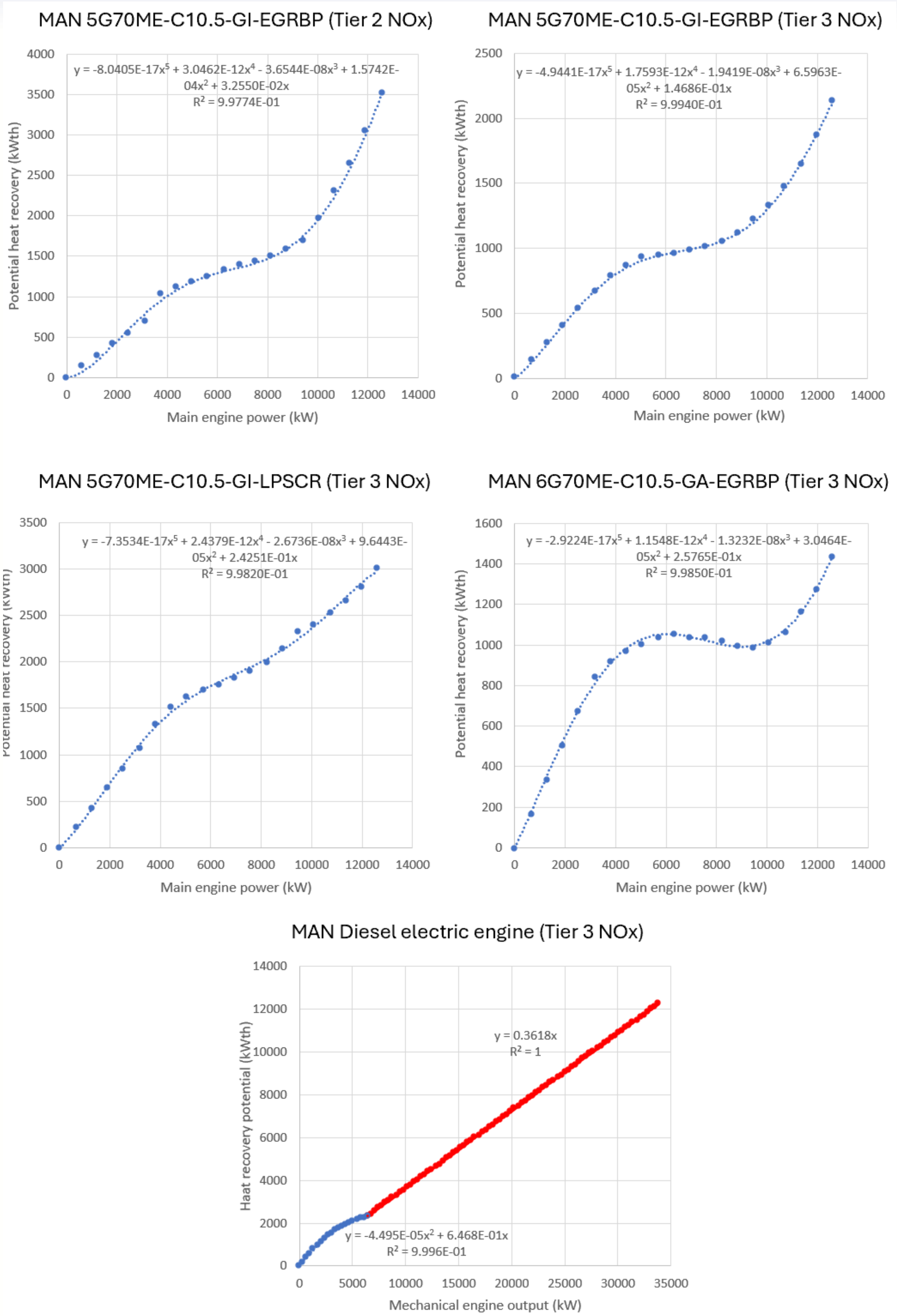


Figure 3, heat recovery potential correlations for all main engine types evaluated in this study.

2.6 Base heat load of the vessel

The total amount of heat that can potentially be recovered from the exhaust gases is not likely to be used exclusively in the carbon capture system. The heat load of the vessel must be subtracted from the recovered energy to determine the energy available for the carbon capture system.

Unfortunately, there is no historical data on the heat load of the chartered LNG carrier available. However, TotalEnergies has shared the design heat loads of the vessel in different conditions, which is used in this study as an estimate of the (constant) heat load at each point in time. Figure 4 shows the base heat load of the vessel in different operation and weather conditions. There seems to be little difference in heat load between operation in Tier 2 or Tier 3 NOx modes, the heat load in ballast mode is slightly higher than in laden mode, and the heat load is higher in winter than in ISO conditions.

Figure 5 shows a more detailed heat load of the vessel in Tier 3 NOx and laden conditions. It becomes clear that most of the heat is used for HFO heating, and accommodation heating in winter. If HFO would be replaced with another pilot fuel (e.g. MGO), more heat would become available for the carbon capture system. Additionally, accommodation heating only requires low quality heat, which could potentially be supplied in another way. Therefore, the base heat load in this study is assumed to be 1000 kWth. A sensitivity study is performed assuming different base heat loads (ranging from 500 kWth to 3000 kWth) to assess the effect of the base heat load of the vessel on the overall performance of the capture system.

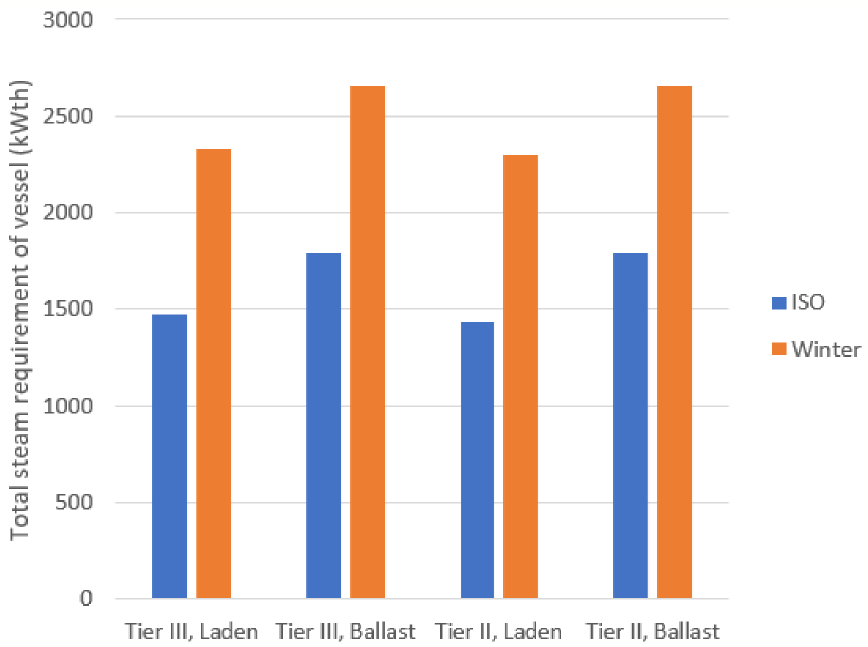


Figure 4, base heat load of the vessel with a differentiation in NOx Tier level, operational mode and seasonal effects.

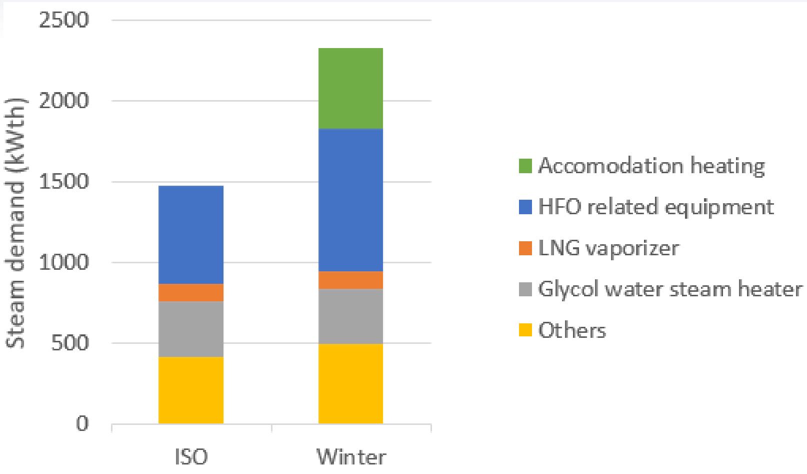


Figure 5, detailed heat load in Tier 3 NOx laden conditions.

2.7 Methane slip correlations

Methane slip has been included in this study for the different engine types, as this can have a large effect on the ship's total CO_2 equivalent emissions. There is not much public data available on methane slip. For the ME-GI and ME-GA engines, data has been acquired from the MAN CEAS datafiles described previously. For the ME-GA engines, only data is available at 75% load. For simplicity, it is assumed that this value is constant over the whole load range. However, it is likely that the specific methane emissions will increase at lower loads, as is also observed for the other engine types. The methane slip for the 4-stroke engines, used for both the diesel electric system and the auxiliary engines, is obtained using correlations from literature (FUMES report [5]). The resulting methane slip correlations can be found in Figure 6. Note that the FUMES report emissions are the only methane slip emissions measured, while the other methane slip data are based on the design emissions for the engines as described by the manufacturers. By far the highest methane slip is caused by the 4-stroke engines, especially at lower loads. The lowest methane slip is observed for the ME-GI engines. These correlations are added to the data analysis to evaluate the methane slip emissions for the considered chartered TotalEnergies vessel.

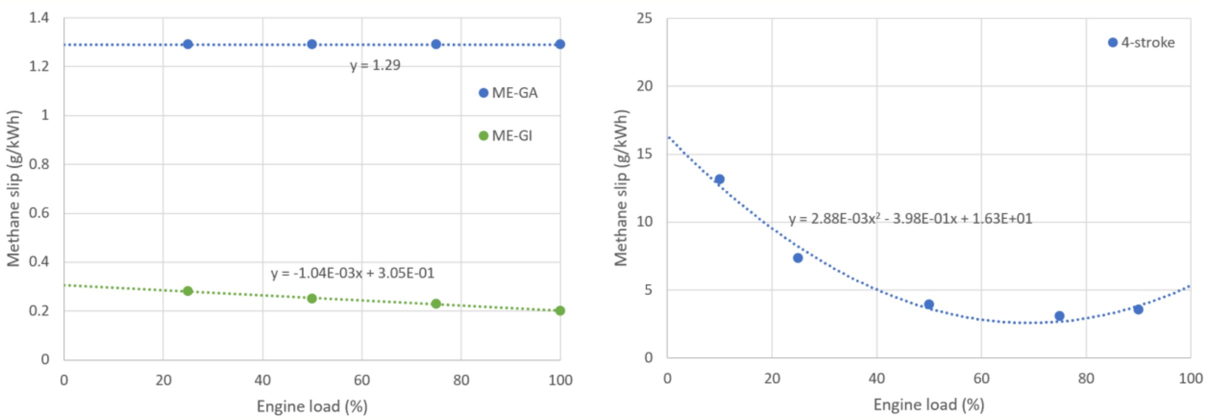


Figure 6, methane slip correlation for the different engine types studied in this work. The left graphs show the correlations for the ME-GA and ME-GI engines and the right graphs shows the correlation for the 4-stroke engines.

3 Data acquisition and methodology for analysing data

Historical operational data has been acquired from the chartered TotalEnergies LNG carrier. 575 days of operational data was supplied at an hourly average resolution. For the main engines, the power consumption of the port and starboard engine is used to calculate the fuel consumption for the different engines considered with the correlations summarized Figure 1. For the auxiliary engines, the gas and HFO flow rates given in the dataset by TotalEnergies are directly used. Additionally, the fuel consumption of the auxiliary boilers and the gas combustion unit (GCU) as described in the TotalEnergies dataset have been considered in the analysis.

The data acquired is used to calculate the CO_2 emissions, heat requirement for the carbon capture system and heat availability for the carbon capture system for each datapoint (every hour) in the dataset. Commercial Visplore data analysis software (v1.7.1) is used to perform the data analysis.

The following methodology is followed for each datapoint in the dataset:

- Calculate the main fuel and pilot fuel consumption for the chosen engine type for each engine on the vessel using the correlations described in Figure 1.
- Calculate the total fuel consumption per fuel type by adding the fuel flow rates of the main engines, auxiliary engines, GCU and auxiliary boilers.
- Calculate the total CO_2 emissions by converting the fuel consumption to CO_2 emissions using the appropriate emission factors (2.75 kg/kg for LNG, 3.206 kg/kg for MGO and 3.114 kg/kg for HFO)
- Calculate the amount of CO_2 to be captured, by selecting a design point for the capture system (e.g. 70% of total flow) and using the methodology indicated in Figure 7, Equation *2* and Equation *3*. Using this methodology will ensure the capture system is used to cover all flue gases at lower engine loads, while covering a part of the flue gas (equal to the design flow rate) during times with higher flow rates than the design flow rate.
- The design point for the capture system should be varied to perform a sensitivity analysis for the performance of the capture system as a function of size of the capture system.
- Calculate the amount of heat required to capture the CO_2 from the exhaust gas. In this study, a constant specific heat demand of 3.5 MJ/kg CO_2 is assumed based on using monoethanolamine (MEA) as the capture solvent. For more advanced solvents, this value could be lower (2.8 MJ/kg CO_2 is assumed for the CESAR1 case)
- Calculate the potential heat recovery from the main engines and auxiliary engines using the correlations shown in Figure 3 and Figure 2 and add these together to obtain the total potential heat recovery from the main and auxiliary engines
- Calculate the available heat from the capture system by subtracting the base heat load of the vessel from the total heat availability.
- Subtract the available heat from the capture system from the total heat requirement of the capture system to calculate the heat that is still required by burning additional fuel. If this value is lower than zero, there is enough heat available to capture 90% of the emissions at that point in time. The surplus heat is not stored in the analysis.

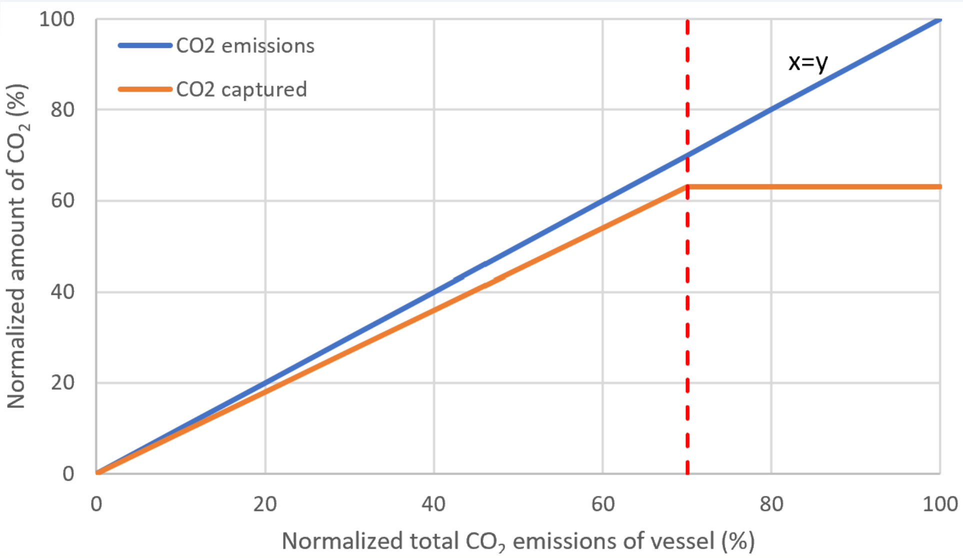


Figure 7, generic representation of the amount of CO_2 captured and the amount of CO_2 in the exhaust gas as a function of total CO_2 emissions of the vessel. The red line indicates the selected size of the capture system, which is a variable in the analysis.

$$m_{CO2,cap} = m_{CO2,exhaust} \cdot \%_{cap}\ (below\ design\ flow) \qquad \text{Equation 2}$$

$$m_{CO2,cap} = m_{CO2,exhaust,design} \cdot \%_{cap}\ (above\ design\ flow) \qquad \text{Equation 3}$$

Following this strategy, the total amount of CO_2 emissions, the total fuel consumption per fuel type, the amount of CO_2 captured, the total heat demand of the capture system and the heat to be supplied by burning additional fuel can be calculated. In the analysis in this work, the frequency of data is every hour, the flow rates are expressed in kg/h and the energy streams are expressed in kW. This means that summing up every hour of data (for the 575 days of data that is available), gives the total flow rates in kg and total energy requirement in kWh.

3.1 Overview of cases studied

An overview of the cases studied can be found in While the electricity demand negatively affects the performance of the capture system leading to higher fuel penalty, the specific electricity consumption (kWh/kg CO2) for the capture system is relatively constant. Therefore, it is not detrimental to exclude the electricity demand for the purpose of comparing cases.

Table 1. Differences in engine types, NOx Tier, base heat load of the vessel, WHRU outlet temperature and capture solvent are evaluated. It is important to note that the electricity demand of the capture and liquefaction system has not been considered for these cases. This is only considered for the final case described in chapter 5. While the electricity demand negatively affects the performance of the capture system leading to higher fuel penalty, the specific electricity consumption (kWh/kg CO_2) for the capture system is relatively constant. Therefore, it is not detrimental to exclude the electricity demand for the purpose of comparing cases.

Table 1, overview of cases studied in the optimization study

Case	Engine	NOx Tier	Base heat load (kWth)	WHRU outlet	Capture solvent

				temperature	
1	5G70ME-C10.5-GI-EGRBP	Tier 3	0	135	MEA
2	5G70ME-C10.5-GI-EGRBP	Tier 3	500	135	MEA
3	5G70ME-C10.5-GI-EGRBP	Tier 3	1000	135	MEA
4	5G70ME-C10.5-GI-EGRBP	Tier 3	2000	135	MEA
5	5G70ME-C10.5-GI-EGRBP	Tier 3	3000	135	MEA
6	5G70ME-C10.5-GI-EGRBP	Tier 3	1000	180	MEA
7	5G70ME-C10.5-GI-EGRBP	Tier 3	1000	135	CESAR1
8	5G70ME-C10.5-GI-EGRBP	Tier 2	1000	135	MEA
9	5G70ME-C10.5-GI-LPSCR	Tier 3	1000	135	MEA
10	5G70ME-C10.5-GA-EGRBP	Tier 3	1000	135	MEA
12	5G70ME-C10.5-GI-LPSCR (-5 °C)*	Tier 3	1000	135	MEA
13	Diesel Electric base case	Tier 3	1000	135	MEA

* For this case, a 5 °C temperature loss of the exhaust gas is assumed because of the SCR system

4 Results of the analysis

4.1 Detailed results for the base case (case 3)

Case 3 is selected as the base case for this study, as it represents the actual engine installed on the TotalEnergies chartered LNG carrier, and considers a base heat load of 1000 kWth.

The calculated data on the total fuel consumption, CO_2 emissions and methane slip can be found in Table 2. Note that the auxiliary engines methane slip is much higher than the main engines methane slip. This is because the auxiliary engines are 4-stroke engines, which have much higher corresponding methane slip. When using a 100-year global warming potential of 30 for methane, the CO_2eq emissions are 7.37 kton, or 8.5% of the total vessel's emissions, which is not negligible. The methane slip emissions are considered in the avoidance calculations.

Table 2, total fuel consumption, CO_2 emissions and methane slip for the base case (case 3).

Parameter	**Unit**	**Value**
Total gas consumption	kton	30.5
Total MGO consumption	kton	0.35
Total HFO consumption	kton	0.65
Total CO_2 emissions	kton	87.0
Total main engine methane slip	ton	33.9
Total auxiliary engines methane slip	ton	211.6
Total main engine + auxiliary engine methane slip CO_2-eq emissions	kton	7.37*

* Assuming a 100-year GWP of methane of 30.

Figure 8 shows a histogram of the total vessel CO_2 emissions, combining the emissions from all fuel used on the vessel. The data is grouped in bins of 200 kg/h, and the number of datapoints within that bin is shown on the y-axis. Most of the operation of the vessel is performed with total vessel CO_2 emissions ranging between 2000-10000 kg/h. Only 0.3% of the data is above 12 ton CO_2/h. Therefore, for the remaining analysis, the sensitivity of the size of the capture system is analysed between 2 and 12 ton CO_2/h.

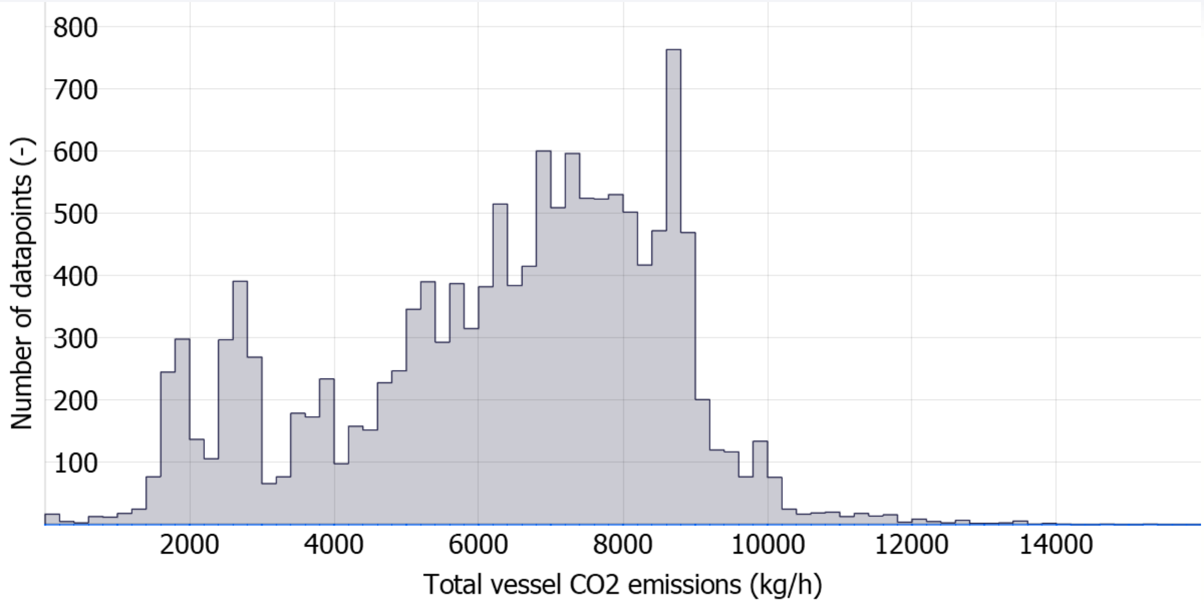


Figure 8, histogram of the total vessel CO_2 emissions. Data is grouped in bins of 200 kg/h.

For the complete operational dataset considered in this study, Table 3 shows the total amount of CO_2 captured, total heat demand of the capture system and deficit of the capture system, for different size of capture systems, ranging from 2 ton CO_2/h to 12 ton CO_2/h. The heat deficit should be supplied by burning additional fuel.

Table 3, total amount of CO_2 captured, heat demand for the capture system and heat deficit of the capture system which requires additional fuel consumption to generate the necessary heat. The columns represent the size of the carbon capture system, expressed in the amount of CO_2 processed per hour in the capture system.

Parameter	**Unit**	**2 ton/h**	**4 ton/h**	**6 ton/h**	**8 ton/h**	**10 ton/h**	**12 ton/h**
CO_2 captured	kton	24.6	46.3	64.4	75.5	78.1	78.3
Heat demand	GWh	23.9	45.0	62.6	73.4	75.9	76.1
Heat deficit	GWh	2.9	14.0	31.4	42.2	44.6	44.8

The assumptions used for the additional gas consumption for heat generation are summarized below:

- Only gas is used for generating heat for the carbon capture system
- There is no methane slip for heat generation in boilers
- The energy density of the gas fuel is 50 MJ/kg
- The efficiency of the heat generator/boiler is 90%
- The specific energy demand of the capture system remains unchanged – i.e., 3.5 MJ/kg CO_2 if using MEA. This is equivalent to assuming that the CO_2 concentration in the exhaust gas of the generator/boiler is similar to the concentration in the main engine exhaust gas

As a final step for the calculations, the emissions caused by the heat generation for the capture system can be included in the capture system. The left part of Figure 9 describes the situation in which no emissions caused by the heat generation are captured, while the right part describes the situation in which the exhaust gas of the heat generation system is injected in the exhaust gas, and is processed in the capture system. This causes additional heat demand for the capture system, which again causes additional emissions. For simplicity, only 1 iteration of this loop is considered in the calculation, while the 2nd iteration of this loop is vented to the atmosphere, as shown in the figure. For both situations, the results are calculated. It is assumed that the capture system can handle these additional exhaust gases, and that still the same specific heat demand of 3.5 MJ/kg CO_2 is required to capture the CO_2. Note that it would be more accurate to solve this as a system of equations, rather than iteration-based calculations. The iteration-based approach is purely used for simplicity in this study.

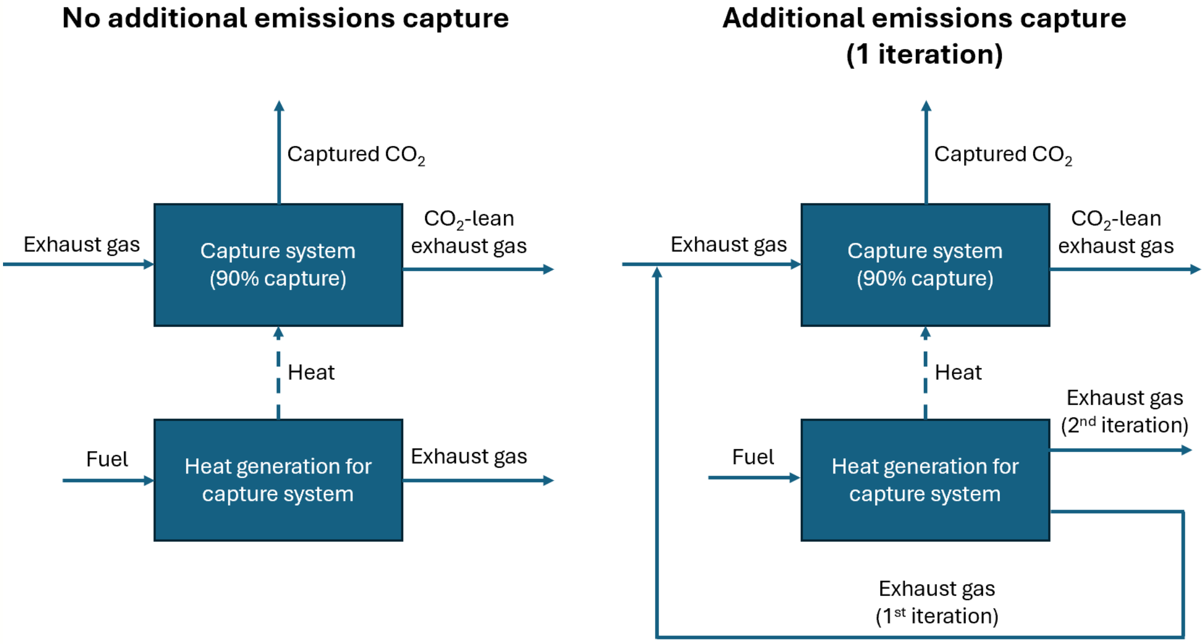


Figure 9, methodology for considering additional capture of emissions caused by fuel usage for heat generation of the capture system.

Using the data in Table 2 and Table 3 and the assumptions described above, the results of the base case (case 3) without capture of the additional emissions caused by heat generation for the capture system are calculated and shown in Table 4. Figure 8 shows the percentage of heat needed for the capture system supplied by the exhaust gas. At the smallest size, the majority (87.9%) of the heat can be supplied by the exhaust gas, while for the largest systems, this drops to ca. 41%. This means that a significant part of the heat must be supplied by burning additional fuel, which gives additional emissions. Figure 11 (blue line) shows the performance curve of the capture system without additional emission capture from heat generation. In this plot, the amount of (on-board) CO_2 avoidance is plotted against the fuel penalty for each size of the carbon capture system evaluated. The fuel penalty is defined as the percentage increase in total fuel demand without and with carbon capture (no differentiation is made for the type of fuel for simplicity). For the smallest size (2 ton CO_2 processed/h), ca. 25% of the CO_2 emissions can be avoided at a fuel penalty lower than 1% (note that electricity demand of the capture system is not considered here). The performance of this case is quite good because most of the heat for the capture system can be recovered from the exhaust gases, causing little additional fuel consumption. However, the performance target of the EverLoNG project is to capture/avoid ca. 70% of the emissions of the vessel. For the system processing 8 ton CO_2/h, the CO_2 avoidance just reaches this 70%, at a fuel penalty of 10.7%. For the larger systems, the avoidance increases marginally, and it is not expected that it is worth designing the capture system for these highest CO_2 capacities.

Table 4, results of the base case (case 3) analysis considering no capture of additional emissions caused by heat generation for the capture system. The columns represent the size of the carbon capture system, expressed in the amount of CO_2 processed per hour in the capture system.

Parameter	Unit	2 ton/h	4 ton/h	6 ton/h	8 ton/h	10 ton/h	12 ton/h
Percentage of original emissions captured	%	28.2	53.2	74.0	86.8	89.7	90.0
Percentage of heat supplied by exhaust gas	%	87.9	68.9	49.9	42.6	41.2	41.1
Additional gas burned for heat deficit	kton	0.23	1.12	2.51	3.37	3.57	3.59
Additional emissions due to heat deficit	kton	0.64	3.08	6.91	9.28	9.82	9.87
Fuel penalty	%	0.74	3.56	7.97	10.71	11.34	11.39
Amount of CO_2 avoided	kton	23.9	43.2	57.5	66.2	68.2	68.4
CO_2 avoidance	%	25.4	45.8	60.9	70.2	72.3	72.5

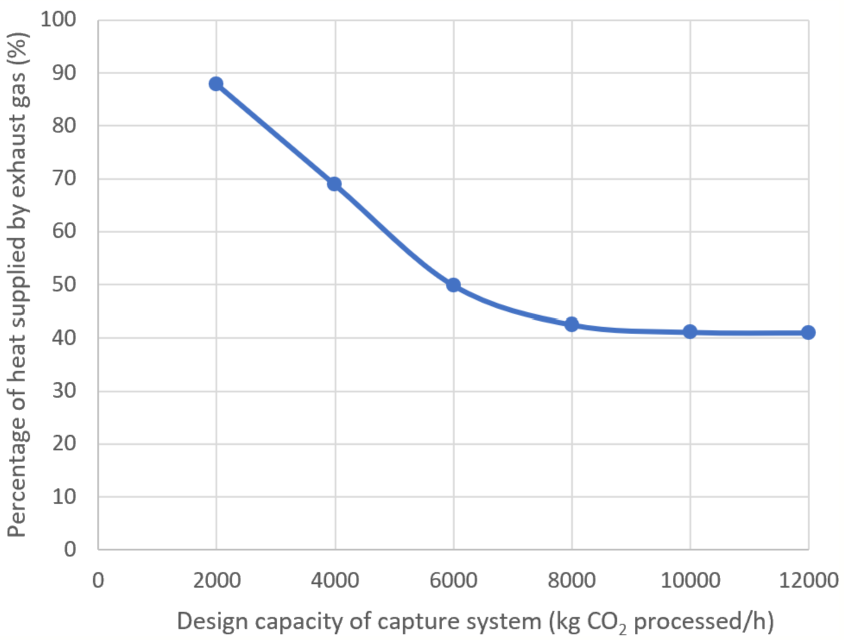


Figure 10, percentage of heat for the capture plant supplied by the exhaust gas

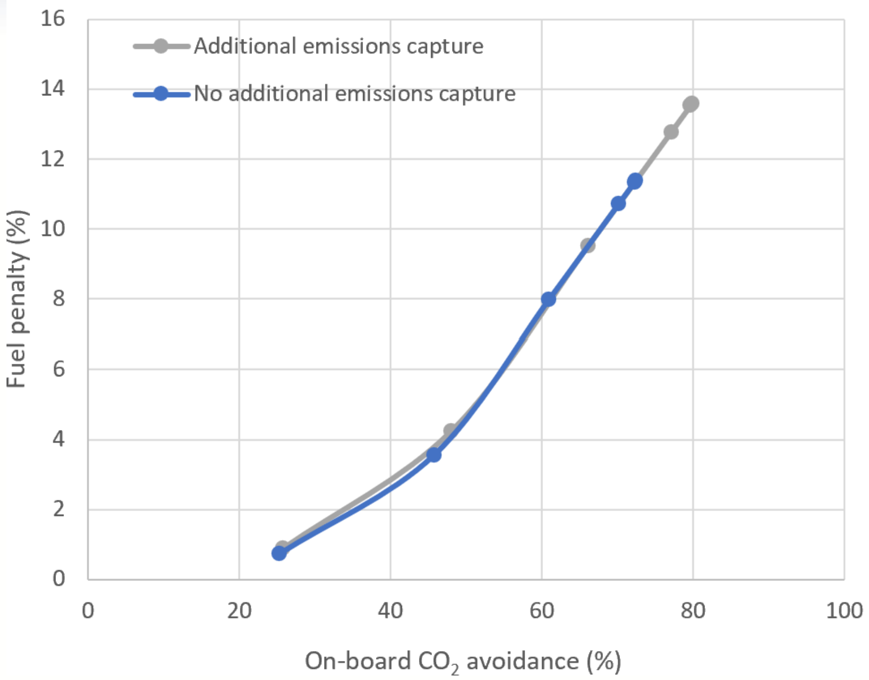


Figure 11, performance curve for the base case (case 3).

The results of the base case (case 3) assuming capture of additional emissions caused by heat generation for the capture system, following the approach described in Figure 9, are shown in Table 5. The effect of this consideration on the performance curve of the capture system is shown in Figure 11 (orange line). The shape of the performance curve remains similar, but higher on-board CO_2 avoidance values can be achieved, up to 80% for the largest system evaluated.

Table 5, results of the base case (case 3) analysis considering capture of additional emissions caused by heat generation for the capture system. The columns represent the size of the carbon capture system, expressed in the amount of CO_2 processed per hour in the capture system.

Parameter	**Unit**	**2 ton/h**	**4 ton/h**	**6 ton/h**	**8 ton/h**	**10 ton/h**	**12 ton/h**
Amount of additional CO_2 captured	kton	0.6	2.8	6.2	8.3	8.8	8.9
Additional energy demand	GWh	0.56	2.70	6.04	8.12	8.59	8.63
Additional gas consumption*	kton	0.04	0.19	0.44	0.58	0.62	0.62
Additional CO_2 emissions	kton	0.11	0.53	1.20	1.61	1.70	1.71
Fuel penalty	%	0.86	4.17	9.36	12.57	13.31	13.37
Amount of CO_2 avoided	kton	24.4	45.5	62.5	73.0	75.4	75.6
CO_2 avoidance	%	25.8	48.2	66.3	77.3	79.9	80.1

Using the same framework as described above, the results for all other cases are calculated and compared to each other.

4.2 Results of comparing different cases

4.2.1 Effect of base heat load of the vessel (case 1-5)

Using the base case engine (MAN 5G70ME-C10.5-GI-EGRBP Tier 3 NOx), the base heat load of the vessel is varied between 0 and 3000 kWth. A 3000 kWth base load is higher than what is ever expected for the vessel following the design heat loads of the vessel shown in Figure 4 and Figure 5 and represents a worst case scenario. Similarly, a heat load lower than 500 kWth is also not expected and represents a very optimistic scenario. Figure 12 shows the percentage of heat required for the capture system that can be supplied by the exhaust gas for the different base heat loads. For the 0 kWth base heat load, close to 100% of the heat can be recovered for the smallest size capture system, and ca. 60% of the heat can be recovered for the largest sizes. With the 3000 kWth base load, the percentage of heat that can be supplied to the capture system is only 5%, and the vast majority of heat needs to be supplied to the capture system by burning additional fuel. Figure 13 shows the corresponding performance curves for cases 1-5. The graphs do not take methane slip into account. For the 8 ton CO_2/h design, case 1 with 0 kWth base heat load gives a fuel penalty of 8.8%, while case 5, with a base heat load of 3000 kWth gives a fuel penalty of 21.1%, showing the importance of heat recovery of the exhaust gas for the performance of the carbon capture system.

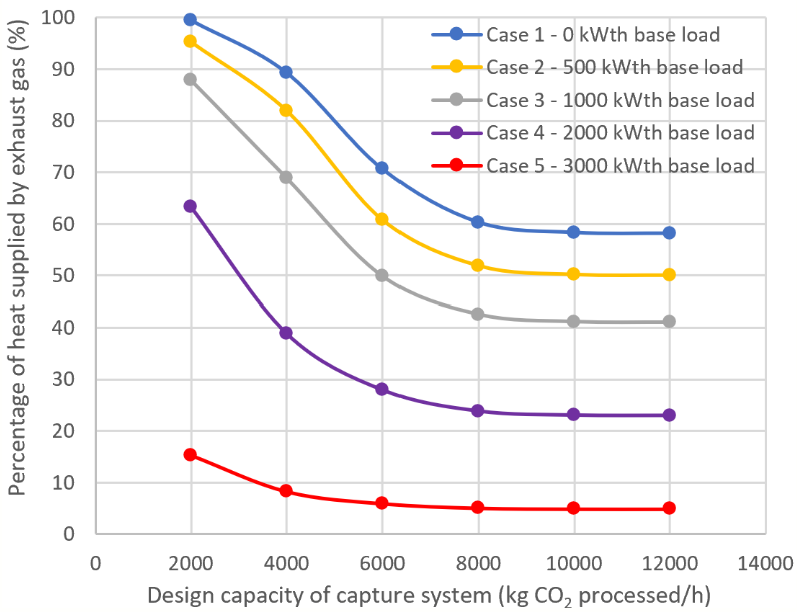


Figure 12, the percentage of heat supplied for the capture system by the exhaust gases for cases 1-5 as a function of the design capacity of the carbon capture system. Methane slip is not taken into account in this graph.

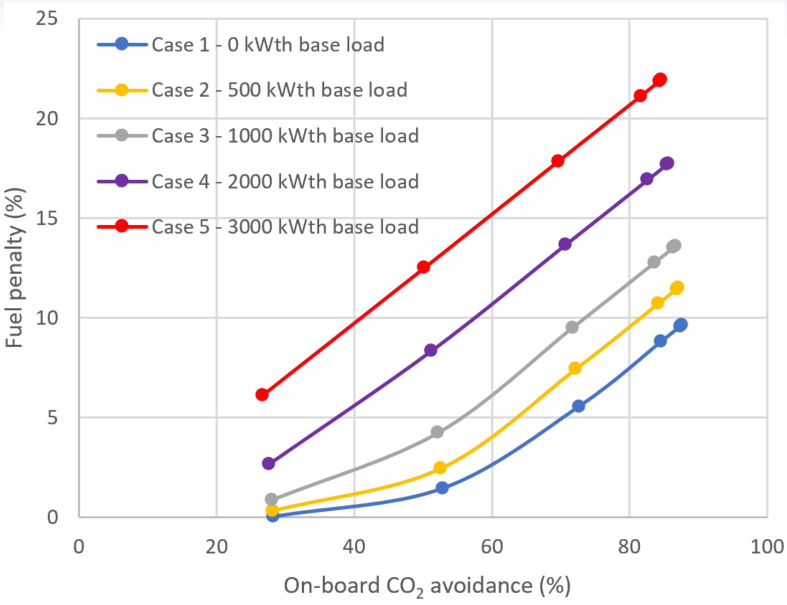


Figure 13, performance curves for cases 1-5. The avoidance numbers exclude methane slip emissions.

4.2.2 Effect of WHRU exit temperature (cases 3 and 6)

An assumption in this study is that the outlet temperature of the WHRU can be decreased to 135 °C instead of the conventional 180 °C often used in the WHRUs. Figure 14 shows the effect of this assumption on the base case (MAN 5G70ME-C10.5-GI-EGRBP Tier 3 NOx; heat load of 1000 kWth). For most sizes of the capture system, the difference in fuel penalty is around 2.5%-points. This significant difference shows that consideration of higher heat extraction rates from the exhaust gases should be evaluated when considering the installation of a carbon capture system.

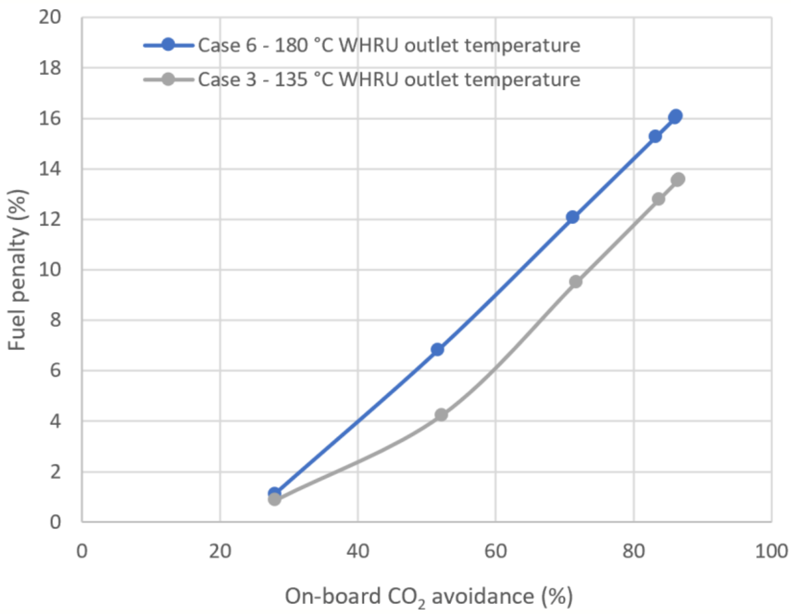


Figure 14, performance curves for cases 3 and 6. The avoidance numbers exclude methane slip emissions.

4.2.3 Potential effect of advanced capture solvent (cases 3 and 7)

For most of the cases, the first-generation MEA capture solvent is considered with a constant specific energy demand of 3.5 MJ/kg CO_2. However, more advanced second generation capture solvents, like CESAR1, have demonstrated lower reboiler duties [6]. A CESAR1 case, assuming a 20% lower reboiler duty (2.8 MJ/kg CO_2) is considered as an additional case. Figure 15 shows the performance curves for the MEA and CESAR1 cases, assuming an identical base case (MAN 5G70ME-C10.5-GI-EGRBP Tier 3 NOx) and identical heat loads of the vessel (1000 kWth) and excluding the methane slip emissions. For a capture system size processing 4 ton CO_2/h (second datapoint from the left), the fuel penalty is 50% lower when considering the CESAR1 solvent compared to the MEA solvent, decreasing from 4% to 2%. This is interesting, as the reboiler duty is only 20% lower for the CESAR1 solvent. This difference is explained in Figure 16, where the heat deficit histograms for both cases are shown. For the MEA case, most heat deficits are in the 0-1000 kWth range. For the CESAR1 case, all these heat deficits become zero and around 50% of the time there is no heat deficit at all, while this is only valid 9% of the time for the MEA case. Looking at the difference in performance in Figure 14, this is still true for larger capture systems (although to a lesser extent). This shows the importance of having such detailed analysis of the operation of the vessel with a potential carbon capture system, showing that a 20% lower reboiler duty might result in a much higher reduction in fuel penalty, depending on the operational profile of the vessel.

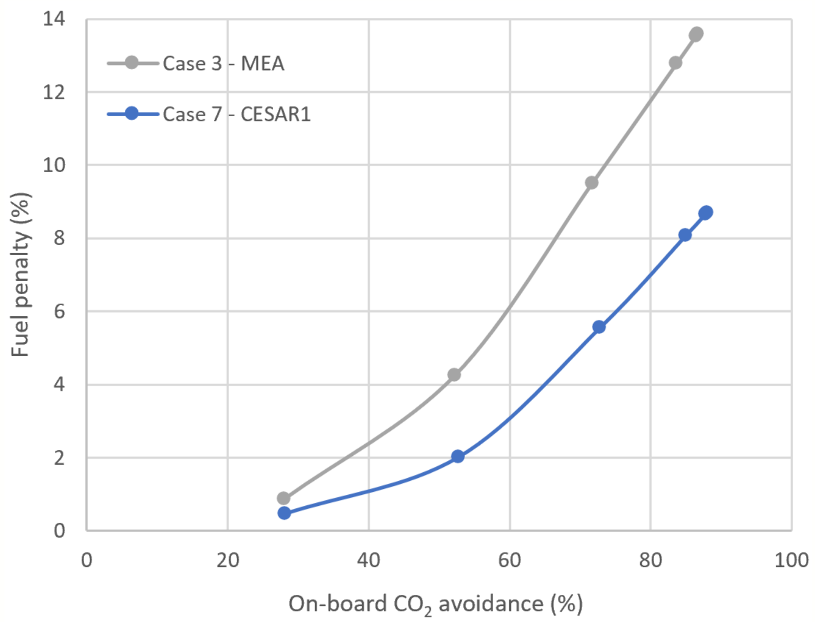


Figure 15, performance curves for cases 3 and 7. The avoidance numbers exclude methane slip emissions.

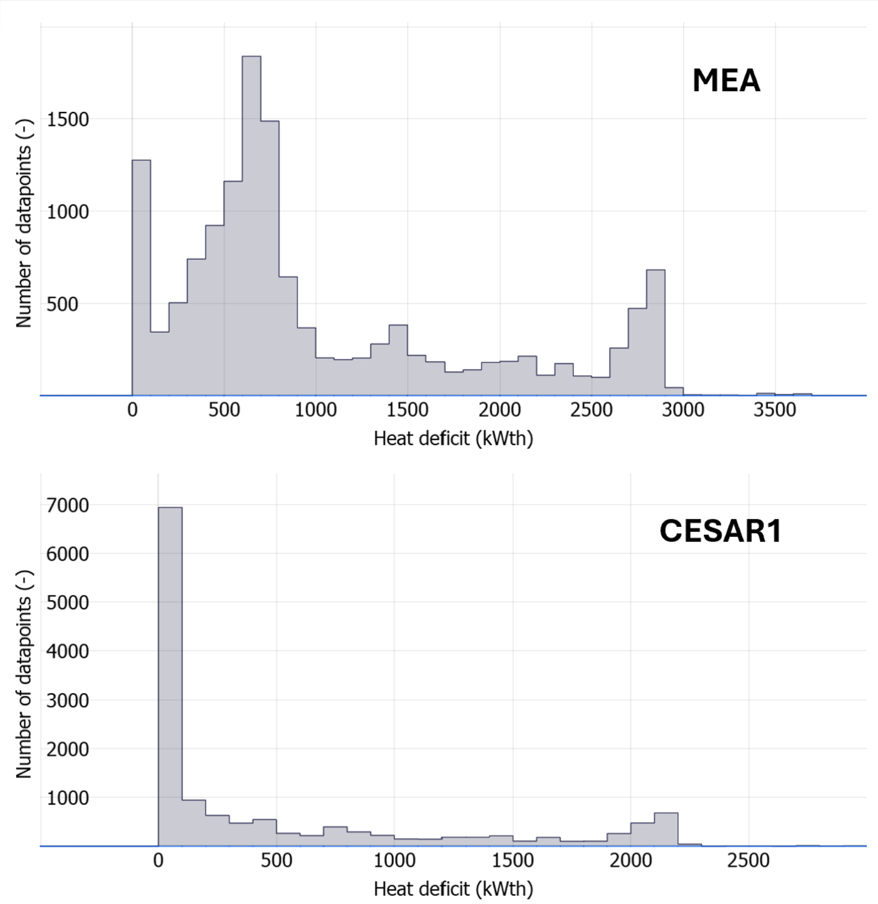


Figure 16, histogram of the heat deficit for the carbon capture system for (top) MEA and (bottom) CESAR1 at a design capacity of 4 ton CO_2/h.

4.2.4 Effect of NOx tier 2 and 3 (cases 3 and 8)

The effect of the NOx tier (2 and 3) is evaluated for the base case engine (MAN 5G70ME-C10.5-GI-EGRBP), assuming identical heat loads of the vessel (1000 kWth) and excluding the methane slip emissions. Note that the performance of the engine is different between Tier 2 and Tier 3 operation. The Tier 3 engine variant performance is taken as the basis in the calculations, and the performance of the Tier 2 engine is compared against this. Figure 17 shows the performance curves for case 3 (tier 3 engine) and case 8 (tier 2 engine). The fuel penalty of the Tier 2 engine is 3%-points lower for the small size capture system and 5%-points lower for the large size capture system. Note that the fuel penalty of the Tier 2 engine goes below zero, because the Tier 3 engine is used as the basis, and the engine efficiency of the Tier 2 engine is higher and thus fuel consumption is lower. Also, this analysis shows that minimizing NOx emissions, while necessary, reduces the performance of a vessel, and also reduces the amount of heat available for the capture system.

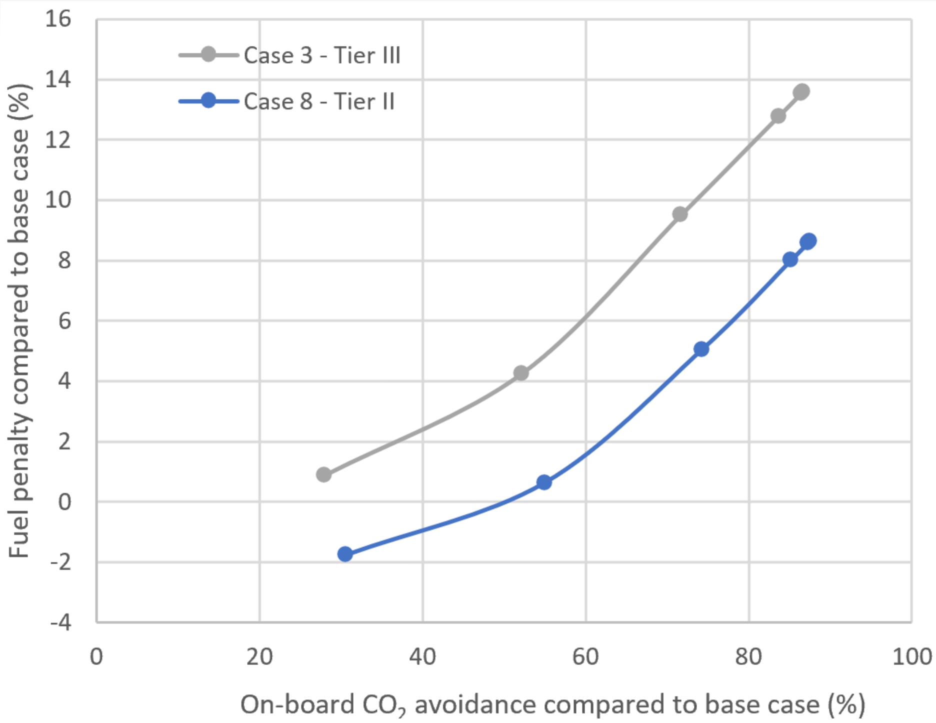


Figure 17, performance curves for cases 3 and 7, using the engine performance of case 3 as the basis. The avoidance numbers exclude methane slip emissions.

4.2.5 Effect of main engine type - 2-stroke comparison (Cases 3, 8, 9, 10, 11, 12)

The effect of the different 2-stroke engines is evaluated. Figure 18 shows the heat recovery potential for every 2-stroke engine considered in this study. The GI EGRBP (Tier 3) engine and the GA EGRBP engine have the lowest heat recovery potential of all engines. This is followed by the GI EGRBP (Tier 2). The highest heat recovery potential is calculated for the GI LPSCR engine, even when a 5 °C temperature loss due to the SCR system is considered. Figure 19 shows the performance curves for all 2-stroke engines, compared to the base case (case 3). Even though the GI LPSCR engine does not have the best engine performance, because of the higher heat availability in the exhaust gas, it gives the best performance (lowest fuel penalty) at high avoidance percentages. The GI EGRBP (Tier 2) has a performance relatively similar to the GI LPSCR engine. The performance curves of the GA EGRBP and GI EGRBP (Tier 3) show higher fuel penalties at the same avoidance rates. These engines are not optimal when considering on-board carbon capture.

Note that Figure 19 does not take methane slip into account. Figure 20 shows the results for case 3, case 10 and case 12 when including and excluding methane slip. GA engines have higher methane slip than GI engines, which results in a higher difference for the GA engines between including and excluding methane slip than the GI engines. However, for the GI engines, the methane slip here is also still quite significant, but this is mainly caused by the auxiliary engines, which cause the majority of methane slip emissions in that case as shown in Table 2.

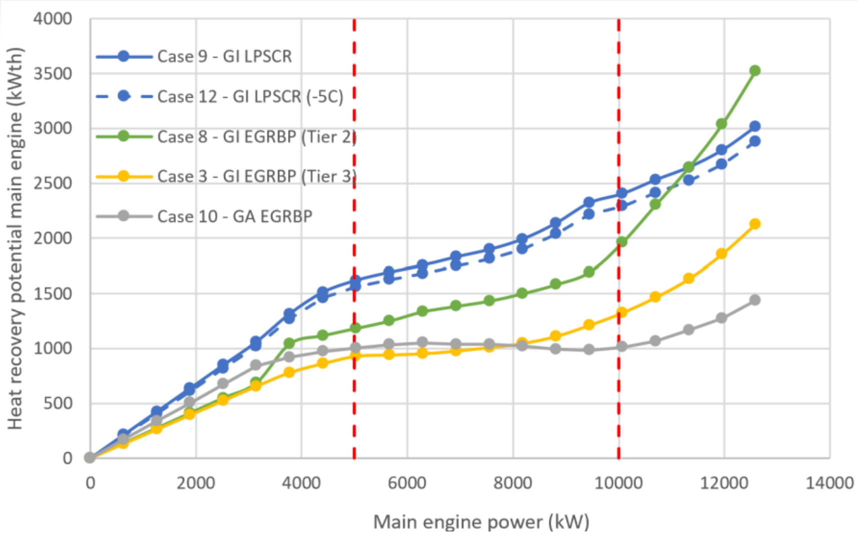


Figure 18, heat recovery potential as calculated for every two-stroke engine considered in this study. The red lines indicate the boundaries of the most relevant engine loads in the operational profile.

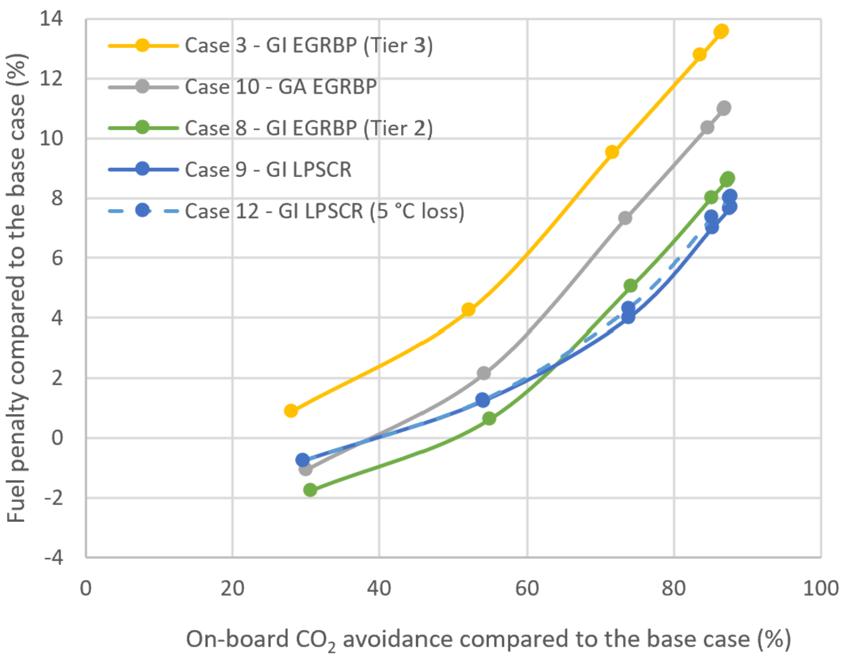


Figure 19, performance curves for every two-stroke engine considered in this study, excluding methane slip.

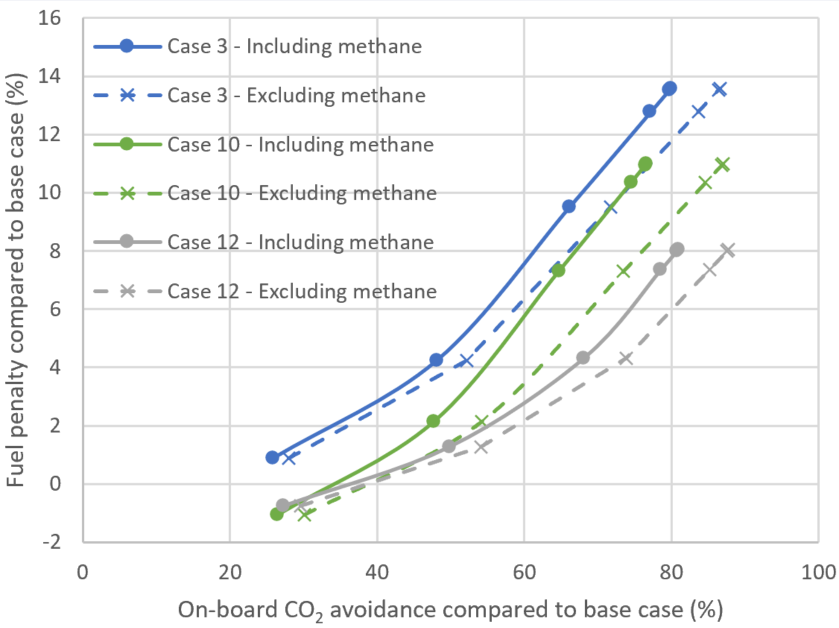


Figure 20, performance curves for cases 3, 10 and 12 without and with consideration of methane slip.

4.2.6 Effect of main engine type (2-stroke versus 4-stroke)

A 4-stroke engine is considered as an alternative to the 2-stroke engines considered in this work. For the four-stroke analysis, the power demand of the main and auxiliary engines is added to a single power demand, for which the relevant parameters (fuel consumption, heat recovery) are determined. The results of the 4-stroke Diesel electric case (case 13) is compared to the base case (case 3) and the GI LPSCR case (case 12) in Figure 21. The 4-stroke diesel electric case shows a better performance than the 2-stroke cases. However, the effect of methane slip is much more pronounced, lowering the avoidance numbers significantly. The main reason that the 4-stroke diesel electric system performs better than the 2-stroke cases is the low efficiency of the original auxiliary engines in the dataset provided by TotalEnergies for their chartered vessel (which negatively affects the 2-stroke cases). Figure 22 shows the specific gas consumption for the auxiliary engines in the dataset, which shows an average around 180 g/kWh, while the 4-stroke main engine has significantly better specific fuel consumption. In discussion with the partners, it was decided to perform a sensitivity where the efficiency of the auxiliary engines would increase by 16.6%, giving an average specific fuel consumption of ca. 150 g/kWh, similar to the performance of the 4-stroke main engines. Figure 23 shows the resulting performance curves of cases 3, 12 and 13. The figure shows that case 3 (base case) now shows comparable results compared to case 13, while case 12 (GI-LPSCR) now shows better performance than the four-stroke system, for every size of carbon capture system.

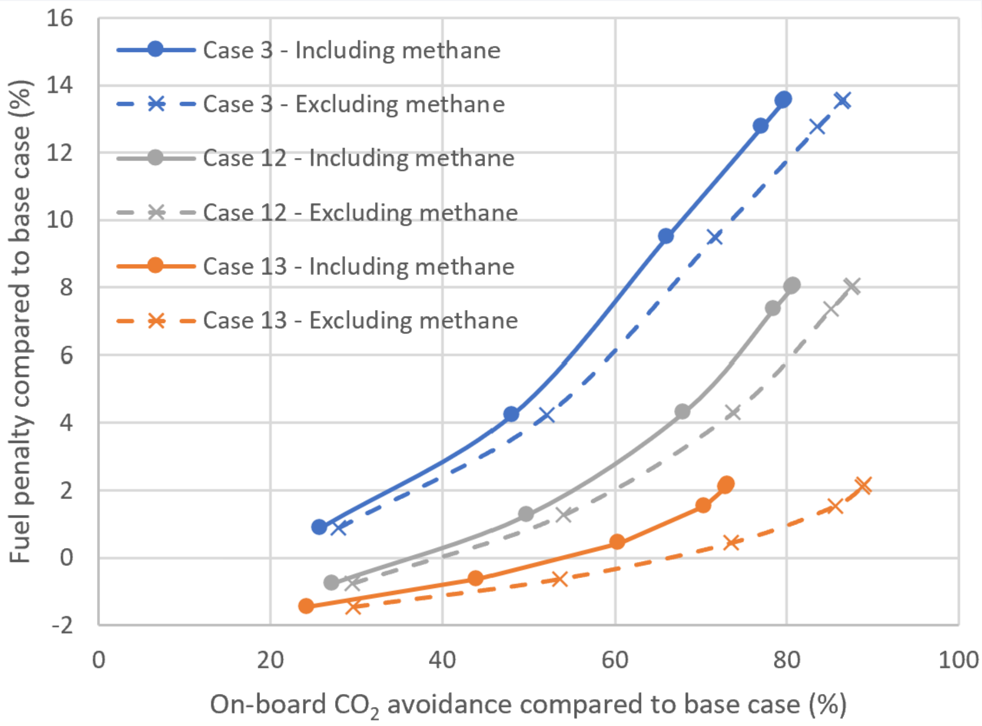


Figure 21, performance curves for cases 3, 12 and 13, without and with consideration of methane slip.

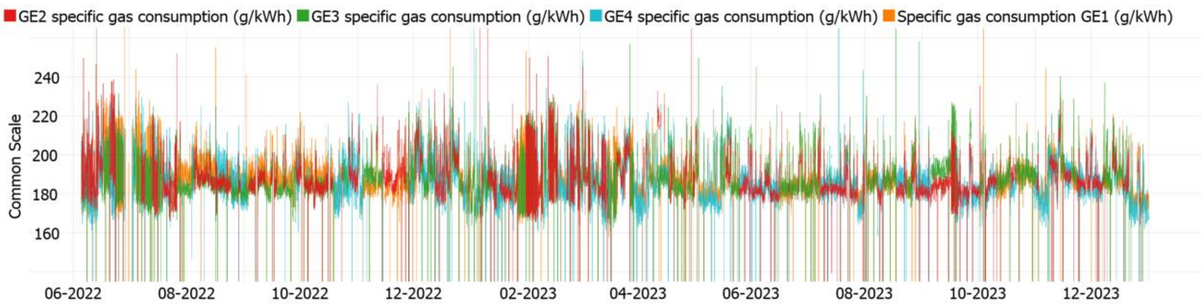


Figure 22, specific fuel consumption of the auxiliary engines in the dataset provided by TotalEnergies.

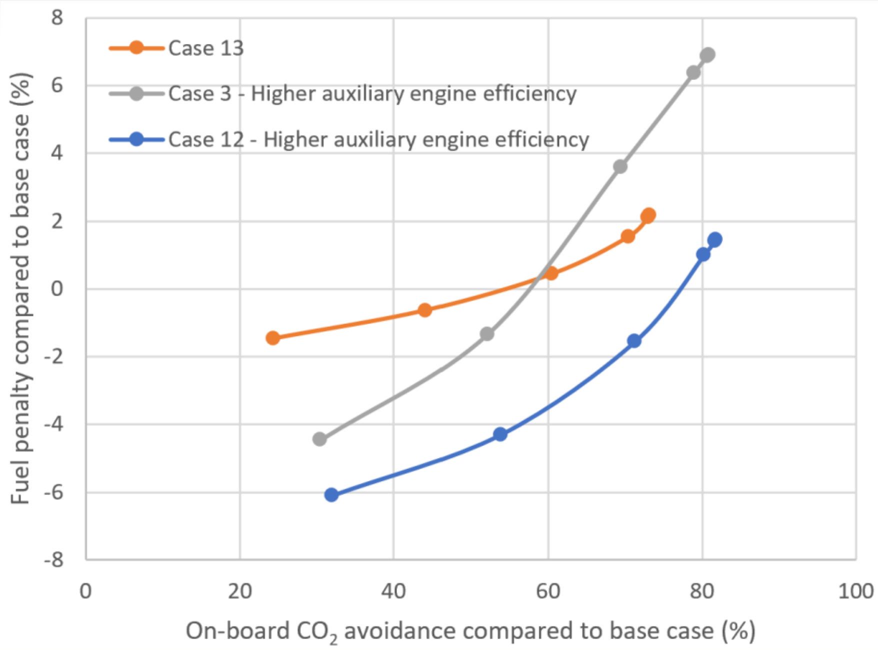


Figure 23, performance curves for cases 3, 12 and 13, with increased auxiliary engine performances for cases 3 and 12. All cases include methane slip.

4.2.7 Conclusions from comparison study

Based on the analysis performed above, the two-stroke GI-LPSCR engine (case 12) shows the best performance when considering an on-board carbon capture system. This engine is selected for a final case study, which provides the final data transferred towards the concept design, TEA and LCA analysis performed in the EverLoNG project. In this final analysis, some changes/optimizations have been applied to the methodology to make it approach reality as close as possible, based on the learnings from comparing all cases in this chapter.

5 Re-analysis of optimal case and results

As mentioned above, the 5G70ME-C10.5-GI-LPSCR engine has been selected for the final case analysis. Some changes have been applied to the analysis that are summarized below:

- The auxiliary engines are implemented differently. In the previous analysis, the gas and pilot fuel flow rates were taken from the dataset provided by TotalEnergies. In the new analysis, the power of the auxiliary engines is taken, and the gas and pilot fuel flow rates are calculated, based on the technical file of the auxiliary engines as provided by TotalEnergies. The correlations used for this are shown in Figure 25.
- HFO has been fully replaced as a pilot fuel by MGO. This way, the base heat load of the vessel can be decreased to 1000 kWth or lower, because there is no more heat requirement for heating HFO. For the analysis, 1000 kWth is used as the base heat load.
- The gas consumption of the GCU is still considered, but gas consumption for the auxiliary boiler is left out based on discussions with TotalEnergies. It is not expected the auxiliary boiler is needed frequently on an LNG carrier. The auxiliary boiler only accounted to ca. 15 ton of fuel use over the whole operational profile supplied by TotalEnergies, which is negligible compared to the total fuel consumption of the vessel.

- The electricity demand of capture system is considered in the analysis. A constant specific electricity consumption is assumed (0.1661 kWh/kg CO_2) based on the simulation results in the EverLoNG project. The efficiency of generating this electricity is also assumed constant at 0.174 kg/kWh, which is the efficiency of the auxiliary engine at 50% load.
- The additional CO_2 emissions caused by electricity generation are considered in the capture system using 1 iteration, similarly to what was done for heat as shown in Figure 9. The updated methodology is shown in Figure 24. Again, note that solving this as a system of equations would yield more accurate results, although this was not considered in this study.
- Methane slip emissions of electricity generation has been considered. Methane slip is assumed constant at 3.93 g/kWh for this additional electricity generation, which is the expected emissions of a 4-stroke auxiliary engine at 50% load, as shown in Figure 6.
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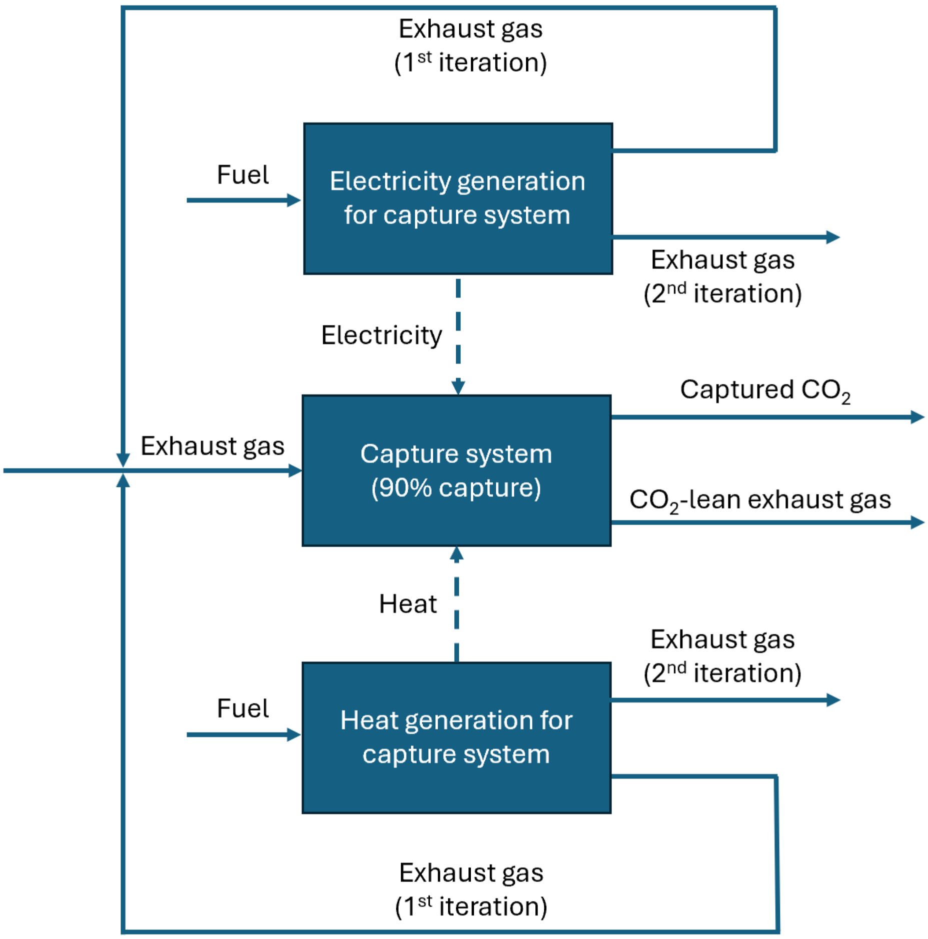

Figure 24, methodology for considering additional capture of emissions caused by fuel usage for heat and electricity generation of the capture system, considered for the final case.

The total fuel consumption, CO_2 emissions and methane slip from the engines as calculated using the correlations for the GI-LPSCR engine in Figure 1, the auxiliary engines in Figure 1 and Figure 25 and the methane slip correlations for the main engine (ME-GI 2-stroke) and auxiliary engines (4-stroke) shown in Figure 6. The new reference vessel CO_2 emissions (83.4 kton) are 3.6 kton lower than the base case reference vessel, which was 87 kton as shown in Table 2. This is mainly because of the improved auxiliary engine performance. The basis for the CO_2 avoidance calculations for the remainder of the report is based on the emissions of this new reference vessel (83.4 kton) and not the old reference vessel. The methane slip is identical to the reference base case, as the same GI type engine is used in the final case, and MAN claims the same methane slip for both engines in the datasheets.

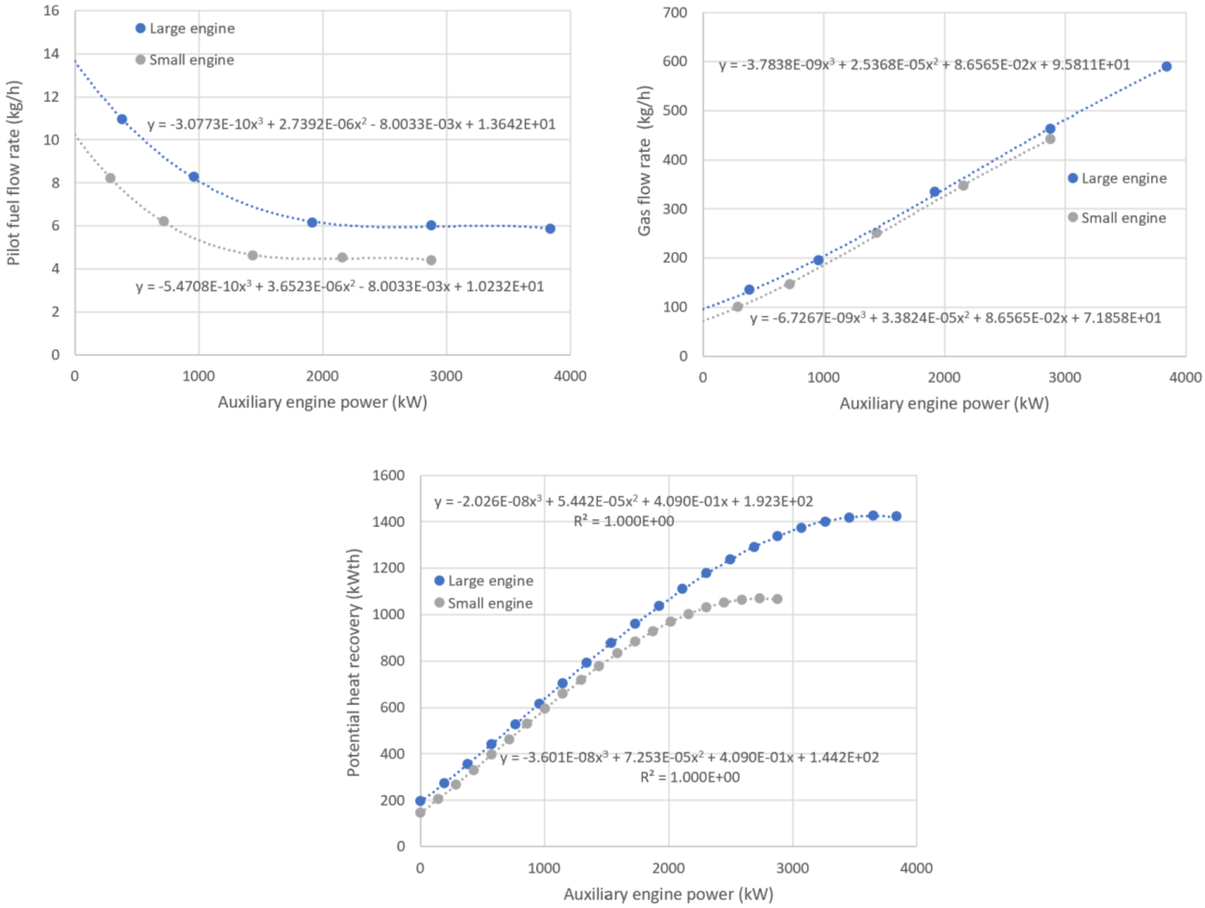

Figure 25, updated auxiliary engine correlations for the final case.

Table 6, fuel consumption, CO_2 emissions and methane slip for the final case reference vessel (without carbon capture)

Parameter	Unit	Value
Total gas consumption	kton	29.4
Total MGO consumption	kton	0.76
Total CO_2 emissions	kton	83.4
Total main engine methane slip	ton	33.9
Total auxiliary engines methane slip	ton	211.6
Total main engine + auxiliary engine methane slip CO_2-eq emissions	kton	7.37*

* Assuming a GWP of 30.

The amount of CO_2 captured, the total heat demand, and total heat deficit are shown in Table 7.

Table 7, amount of CO_2 captured, heat demand and deficit values extracted from the Visplore analysis for the final case. The columns represent the size of the carbon capture system, expressed in the amount of CO_2 processed per hour in the capture system.

Parameter	Unit	2 ton/h	4 ton/h	6 ton/h	8 ton/h	10 ton/h	12 ton/h

CO_2 captured	kton	24.6	45.9	63.4	73.2	74.9	75.0
Heat demand	GWh	23.9	44.7	61.6	71.1	72.8	72.9
Heat deficit	GWh	0.9	3.1	10.0	19.2	20.8	21.0

Using the values in Table 7, the final performance parameters for the Total LNG carrier when considering CO_2 capture are calculated, following the methodology described in Figure 24 and using the assumptions described above. The performance plot of the final case is shown in Figure 26, taking the final engine as the basis (blue line) and the base case engine (case 3) as the basis (grey line). Based on this curve, the 8 ton/h datapoint is chosen as the final case to be studied, as this is the first datapoint above 70% capture/avoidance, which is the target rate of the EverLoNG project. Including all utilities, this will lead to a fuel penalty of 15.4%, or 10.7% when comparing it to the base case. Out of this 15.4%, 8.0% is fuel penalty caused by electricity demand of the capture and liquefaction system, and 7.4% is caused by the heat demand of the capture system. This is for a case where 73.1% of the heat required for the capture system is recovered from the exhaust gases on average. This means that even if all heat can be recovered from the exhaust gases, the electricity demand of the capture and liquefaction system still generate significant fuel penalties. There are however some optimizations possible (in the liquefaction system) compared to the simulations performed in this work, which could reduce this fuel penalty due to electricity demand slightly.

Table 8, results of the final case. The 8 ton/h results are used for the TEA and LCA analysis. The columns represent the size of the carbon capture system, expressed in the amount of CO_2 processed per hour in the capture system.

Parameter	Unit	2 ton/h	4 ton/h	6 ton/h	8 ton/h	10 ton/h	12 ton/h
Main and auxiliary engine exhaust gases only							
Amount of CO_2 captured	kton	24.6	45.9	63.4	73.2	74.9	75.0
Percentage of heat supplied by exhaust gas	%	96.2	93.0	83.8	73.1	71.4	71.3
Gas burned for heat generation	Kton	0.07	0.25	0.80	1.5	1.67	1.68
Emissions due to heat generation	kton	0.20	0.68	2.19	4.2	4.58	4.61
Gas burned for electricity generation	kton	0.71	1.33	1.83	2.1	2.16	2.17
MGO burned for electricity generation	kton	0.013	0.024	0.034	0.039	0.040	0.040
CO_2 emissions for electricity generation	kton	1.99	3.73	5.14	5.93	6.07	6.09
methane slip ($CO_{2,eq}$) for electricity generation	kton	0.48	0.90	1.24	1.43	1.47	1.47
Amount of CO_2 avoided	kton	22.4	41.5	56.1	63.0	64.2	64.3
Fuel penalty	%	2.6	5.3	8.8	12.2	12.8	12.9
CO_2 avoidance	%	24.1	44.8	60.4	67.9	69.1	69.3
Taking additional emissions from heat and electricity generation into account (1 iteration)							
Additional emissions captured	%	2.0	4.0	6.6	9.1	9.6	9.6
Additional heat demand	GWh	1.9	3.9	6.4	8.9	9.3	9.4
Additional gas burned for heat generation	Kton	0.15	0.31	0.51	0.71	0.75	0.75
Additional emissions for heat generation	kton	0.42	0.85	1.41	2.0	2.05	2.06

Additional gas burned for electricity generation	kton	0.06	0.11	0.19	0.3	0.28	0.28
Additional MGO burned for electricity generation	kton	0.0010	0.0021	0.0035	0.0048	0.0051	0.0051
Additional CO_2 emissions from electricity generation	kton	0.16	0.32	0.54	0.74	0.78	0.78
Additional methane slip ($CO_{2,eq}$) for electricity generation	kton	0.04	0.08	0.13	0.18	0.19	0.19
Amont of CO_2 avoided	kton	23.2	43.3	59.3	67.8	69.3	69.4
CO_2 avoidance	%	25.60	47.8	65.4	74.8	76.4	76.5
Fuel penalty	%	3.3	6.7	11.2	15.4	16.2	16.3
Comparing results to base case emissions and fuel consumption (Table 2)							
CO_2 avoidance	%	28.5	49.8	66.7	75.7	77.3	77.4
Fuel penalty	%	-0.9	2.3	6.6	10.7	11.4	11.5

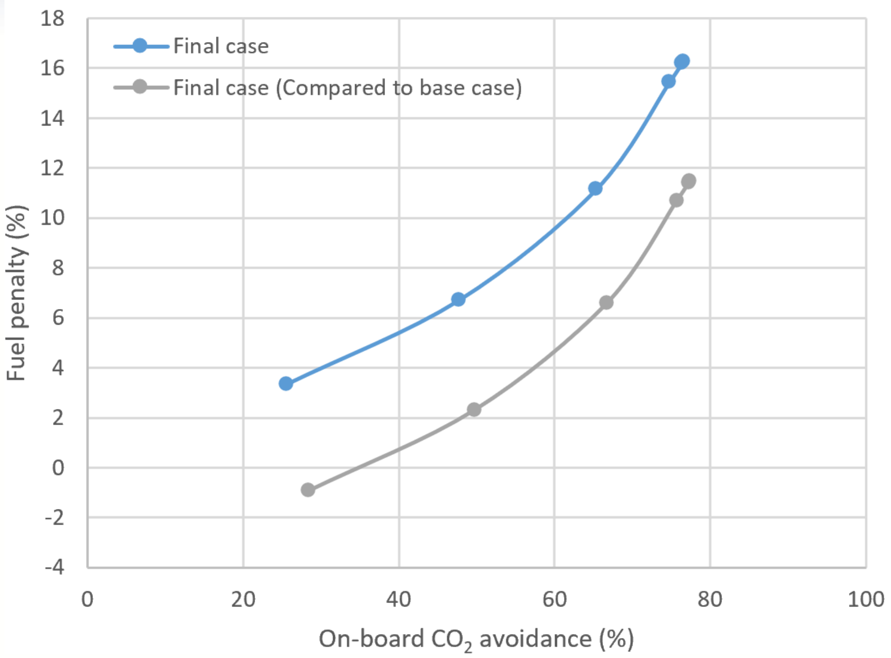

Figure 26, performance plot of the final case compared to the same engine (GI-LPSCR engine) without OCC in blue, and performance plot of final case compared to the base case (GI-EGRBP engine) in grey.

6 Conclusions and recommendations

This report has discussed the optimization of engine systems with on-board carbon capture for a new-build LNG carrier.

A novel methodology was developed that uses (historical) operational data from a vessel to generate a digital cousin of the energy system of the vessel when considering on-board carbon capture. The main resulting metric is a performance curve, where the on-board CO_2 avoidance is plotted against the fuel penalty of implementing the carbon capture system for several sizes of the capture system.

For the base case engine considered in this study, several cases were worked out, varying the NOx tier, WHRU outlet temperature, amine type and base heat load of the vessel:

- **NOx tier**: The tier 2 engine, allowing higher NOx emissions, showed better performance than the tier 3 engine (ca. 4%-points lower fuel penalty). However, higher NOx leads to solvent degradation problems in the capture system, so it is not obvious that operating in tier 2 mode will yield a better overall performance
- **WHRU outlet temperature**: If the outlet temperature of the WHRU unit can be reduced to e.g. 135 °C as LNG has low SOx levels, the performance of the capture system would increase as the fuel penalty decreases with ca 3%-points.
- **Amine type**: If an advanced solvent with a 20% lower energy demand could be considered compared to MEA, this could reduce the fuel penalty significantly by 2-5%-points, depending on the size considered for the capture system. Assessing suitable and efficient capture solvents for on-board carbon capture remains an underexplored topic for now.
- **Base heat load of the vessel**: The heat load of the vessel has a big effect on the performance of the complete system, and the best- and worst-case scenario show a 10-13%-points difference in fuel penalty, depending on the size of the system considered. It is recommended to minimize the users of high temperature heat on the vessel, to allow maximum usage of heat in the capture system. In this study, MGO replaced HFO as a pilot fuel, so HFO heating is not required.

Comparing the different MAN 2-stroke and the MAN 4-stroke engines shows that the 2-stroke engine equipped with a low-pressure SCR system gives the best performance at high (>70%) avoidance rates. Even though the engine efficiency of the low-pressure SCR configuration is lower than the other engines, the higher exhaust gas temperature allows for more recovery of heat for the capture system, yielding an overall better performance of the combined system. This engine configuration is most promising and is selected for further calculations.

More detailed calculations with this final configuration indicate that the optimal size for the capture system processes up to 8 ton CO_2/h of the flue gas. At this size, the capture system can avoid 75.7% of the on-board emissions, at a fuel penalty of 10.7% compared to the base case. In this case, 73.7% of the heat required for the capture system is recovered from the exhaust. Both the remaining heat demand of the capture system and the electricity demand of the capture system contribute equally to the resulting fuel penalty.

The results of this study are forward to the TEA and LCA exercises of the project, where the design is further detailed.

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