Heat Pump as an Emission Reduction Measure for Ships: Environmental and Economic Assessment

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Abstract

Greenhouse gas regulations from the International Maritime Organization, such as the Carbon Intensity Indicator and the Energy Efficiency Existing Ship Index are drawing attention to the implementation of energy efficiency technologies in ships to lower emissions. Presently, more attention is paid to energy efficiency measures related to propulsion (e.g. speed management) and auxiliary energy use (e.g. onshore power). This study compares the environmental impact and cost of replacing heat pumps as an energy efficiency measure instead of oil-fired boilers for two case study vessels by comparing the life cycle impact of different strategies to fulfill the thermal load of vessels while at the port. In terms of life cycle emissions, the heat pump operated using onshore power has the potential to reduce global warming potential by 88% compared to an oil-fired boiler. This accounts for saving 3% and 8% of annual greenhouse gas emissions from entire ship operations, including emissions from engines for the respective case study ships. In addition, shifting to a heat pump avoids NOx and SOx emissions, which adversely affect air quality in the populated areas near the port. Cost results show that the heat pump has an overall higher cost of ownership for case study vessel 1 and a lower cost of ownership for case study vessel 2 compared to oil-fired boiler. Depending on the energy use of specific ships, heat pumps can be cost-competitive at existing carbon emission allowance prices (approximately 90€/tCO_2) in the European emission trading system. For the assessed cases, with the emission trading scheme, the return on investment is less than six years and three years for case study vessels 1 and 2 respectively. The study also shows that operating a heat pump is more cost-effective than directly using electro-fuel in a boiler for thermal loads.

Keywords: Heat pump, Life cycle assessment, Cost assessment, Maritime, Energy efficiency.

1. INTRODUCTION

The shipping industry as a whole is responsible for a significant portion of the global greenhouse gas emissions due to its heavy reliance on fossil fuels. In addition to greenhouse gas emissions, air emissions from shipping, such as nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM), have significant negative impact on both air quality and human health [1]. Impacts of air pollutants are especially critical for ships operating near populated areas such as ferries and cruise ships. When it comes to emission reduction measures from shipping, the focus is typically placed on the propulsion system and auxiliary loads rather than on the hotel heat load as the energy required for the hotel load is significantly less for most ship types. However, the hotel system for passenger ships is responsible for approximately 40 percent of the total energy consumption on board [2].

The International Maritime Organization (IMO) has regulations to reduce GHG emissions for shipping including the Carbon Intensity Indicator (CII), Energy Efficiency Existing Ship Index (EEXI), and Ship Energy Efficiency Management Plan (SEEMP) by promoting energy efficiency measures [3]. In the Fit for 55 legislative packages, the European Union (EU) adopted the FuelEU maritime regulation, which aims to increase the use of renewable and low-carbon fuels in the maritime sector and includes the shipping sector in the EU emission trading scheme (ETS) [4, 5]. In line with these, an increased number of studies have focused on alternative fuels and propulsion systems for ships [6]. Such changes in the ship system also imply changes in the availability of waste heat which is used extensively now for hotel loads, e.g. the waste heat will not be available with onboard reforming requirements [7] or electrification using fuel cells or batteries [8].

Presently the thermal energy for the hotel load is supplied largely from the waste heat from the engines and partially from the onboard auxiliary boiler [9]. The heat from auxiliary oil boilers is mainly required when the main engines are not operating while staying at the port or during winters when the hotel load is high [9]. In sectors such as industry, residential, and building, the role of heat pumps has been considered important for

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decarbonization and energy efficiency, and recent improvements in performance has made heat pumps cost-competitive in these sectors [10]. However, in the shipping sector, few studies [9, 11, 12] have considered heat pumps as energy efficiency measures or emission reduction measures. With the increased interest in the electrification of ferries, heat pumps have been investigated by designers for marine applications. However, the main barrier to the use of heat pumps for larger ships is likely the low utilization of the auxiliary heat generation system owing to the availability of waste heat from engines and the high investment cost [11].

Heat pump feasibility would be different with the two new regulations on the horizon: 1) the ships moored at the quayside of the member state shall be connected to onshore power (OSP) supply for their electrical power demand [13] and 2) the cost of emission allowances within the EU ETS for GHG emissions from shipping [5]. In addition, to meet the GHG emission reduction targets set by the IMO, reliance on lower-priced fossil-based fuels should be reduced and the use of alternative fuels may increase in the future. None of the prior studies considered these factors, and there is a lack of life cycle knowledge on the application of heat pumps on ships, making it difficult to understand their environmental impact over the life cycle. The purpose of this study is to fill this gap by performing life cycle assessment and cost assessment considering scenarios including the above upcoming policies and future scenarios of using an electro-fuel instead of fossil fuel. The study is performed for two case study passenger ships to understand the variation in results between ships based on their operation and size.

2. METHODOLOGY

2.1 Case study ships

Two case study roll-on/roll-off passenger (RoPax) ferries with two different operation profiles and sizes were chosen for the life cycle assessment and costing. Table 1 summarizes the vessel parameters used in the assessment. Case 1 involves a vessel operating between Gothenburg, Sweden, and Kiel, Germany. The energy data for this vessel is obtained directly from the operator. Case 2 vessel operates between Oslo, Norway, and Kiel, Germany, and energy-use data is published by Brakken et al. [9]. Ships differ in terms of the time spent in ports, where boilers are predominantly used, and exhibit varying thermal loads. In addition, the thermal load varies widely for these vessels with seasons, with winter having a higher thermal load and summer having a lower thermal load for hotels. For instance, for case 1, the boiler consumes approximately 2% in summer and approximately 4% in winter of the total fuel used onboard. However, for simplification, the total annual energy use (including both summer and winter conditions) is considered for the assessment with a steady state for both vessels and only when the ship is at the port. Another assumption is that the heat demand is required only on ports as the excess heat from the engine is available while sailing at sea. It may be noted that during extreme winter days, the boiler needs to be operated while at sea which is not considered in this study. Heat pump and boiler power requirements listed in Table 1 were sized with an additional 20% more power than the measured peak demand. The purpose of this excess capacity is to ensure that heat can be supplied even in extremely cold climates.

Table 1: Key characteristics of the case study Cruiseferries

	Case 1	*Case 2*
Gross tonnage (GT)	52000	75 000
Passenger capacity (Number)	1300	2770
Vehicle capacity (cars)	1290	750
Length (m)	240	224
Width (m)	29	35
Connected to OSP	Yes	Yes
Peak thermal power (kW)	6000	4500
Annual thermal load at port (GJ)	156 000	288 000

2.2 Scenarios

Based on the three system configurations and two fuels, five scenarios are assessed to compare the results as shown in Fig. 1. In the first scenario (S1), the policy scenario when the ship is connected to the OSP and an air-to-water heat pump operates using the electricity from OSP. In the second scenario, it is assumed that the heat pump operated from the electricity produced by the auxiliary engines installed onboard. The second scenario is assessed in two parts: the first part (S2a) where the auxiliary engines are fueled using marine gas oil (MGO) and the second part (S2b) where the auxiliary engines are fueled by an alternative fuel. Electro-methanol is considered as the alternative fuel. In the third scenario, an oil-fired boiler is used for the thermal load. Similar to the second scenario, the third scenario is also divided into two parts. The first part (S3a) is a reference scenario or base scenario replicating the present situation where MGO is used as fuel in the boiler and the second part (S3b) considers electro-methanol as the fuel for the boiler. Electro-methanol is preferred over other electro-fuels such as electro-ammonia, electro-hydrogen, and electro-methane because of its lower safety risks for onboard passengers [8]. The influence of the EU ETS for all the scenarios is included in the sensitivity analysis.

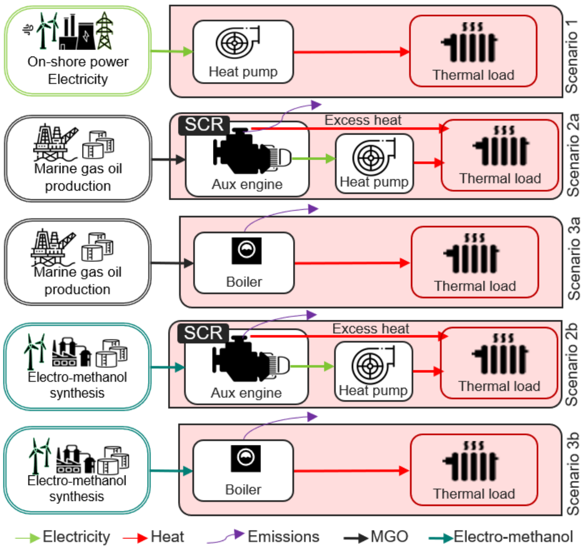

Figure 1: Five scenarios of heat system configurations accessed in the study Scenario 3a is base case scenario.

2.3 Environmental assessment

The environmental assessment of products and services can be evaluated over their lifecycle using the life cycle assessment (LCA) method, which is an established method usually performed under the framework provided by ISO 14040 and ISO 14044. In this study, the main focus is on the emission of GHGs over the life cycle (the extraction of raw material required for producing the component and fuel to the end of life and final use of energy in the ship). The functional unit of the assessment is 'the annual thermal energy required for the ship while at the port'. The scope is limited to the operation of a heat pump or boiler in the port by analyzing the operation profile and measured in 'GJ of energy'. As per earlier studies and analysis of the operation profile, during navigation at sea, excess heat from the main and auxiliary engines is sufficient to meet the thermal demand and the boiler is not operated. In addition, a comparative LCA is performed, hence only the major changes between different configurations are considered in the system boundary as the goal of the study is to provide insight into the environmental impact focusing on GHG emissions specifically addressing the use of heat pumps while ships are moored at ports.

Inventory analysis is performed by dividing the processes into foreground and background processes, where the foreground processes are processes that are focused on the study, and background processes are other processes whose inventory data are adopted from secondary datasets such as Ecoinvent (for raw materials and infrastructure) [14], GaBi (for electricity) [15] and various studies. The inventories used for the assessment are listed in Table 2. The life cycle emissions for the considered system are divided into three parts for simplification as shown in Fig. 2: i) Upstream including the production and distribution of the fuels and electricity generation and distribution usually referred to as well-to-tank. ii) Downstream including emissions from the boiler or auxiliary engine, no emissions are assumed from the heat pump operation, and iii) Manufacturing of the system components such as the oil boiler and heat pump.

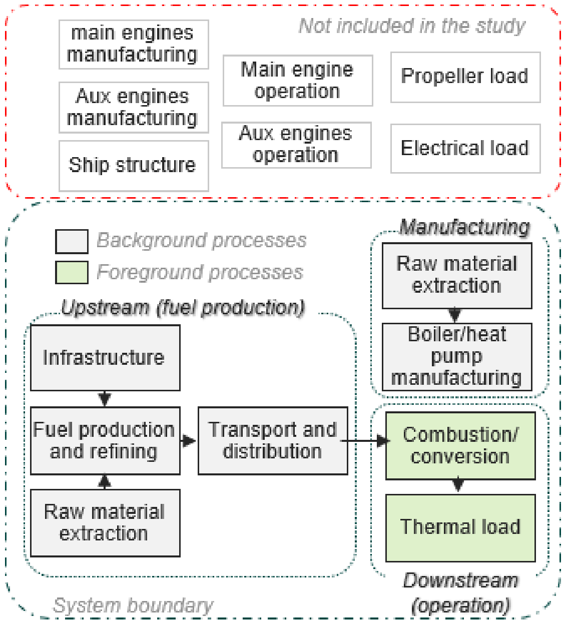

Figure 2: System boundary considered in the study showing background and foreground processes.

In the upstream stage for S1, the GHG intensity of the electricity mix varies with the port where the ship is moored (Gothenburg and Kiel for case 1, and Oslo and Kiel for case 2). Hence the GHG intensity of the electricity mix in Sweden, Norway, and Germany for Gothenburg, Oslo, and Kiel respectively are used. GHG intensity of the electricity mix for Sweden and Norway considered in this study is 30gCO_2eq/kWh [16, 17], and 280gCO_2eq/kWh for Germany [16]. The global volume-weighted average GHG intensity for crude oil production and refining is used (17.6 gCO_2eq/MJ) for the MGO production phase [18]. For electro-methanol production, it is assumed that the fuel would be produced from renewable electricity and is adopted from the study [8] and has a GHG intensity of (-)60gCO_2eq/MJ. The reference study for electro-methanol has included the cradle-to-grave impact of producing electro-methanol including the impacts from the infrastructure (electrolysis, direct air capture, and methanol synthesis), generation of electricity required for various processes, production of consumables required for the processes, and process emissions. The negative value is because the CO_2 used in fuel production is sourced from direct air capture, where CO_2 is removed from the air and stored in the fuel [8].

Downstream, the main emissions are from auxiliary engines used to produce electricity for the operation of the heat pump for S2a and S2b, and for S3a and S3b the emissions are from oil boilers. Both vessels are fitted with selective catalytic reduction for NO_x abatement to meet the Tier 3 requirements. The emissions from engines and boilers 'per engine output, in kWh' are adjusted to the energy of the fuel 'per MJ fuel used'. MGO with 0.1 % sulfur content is considered with 75.08 g of CO_2, 0.05 g of SO_x, and 0.05 g of NO_x (after abatement) for 1 MJ of MGO burned (LHV of 42.7MJ/kg is assumed) [6, 19]. For 1 MJ of methanol, 69.10 g of CO_2 emission is considered. Other GHGs (methane and nitrous oxide) are not considered. These are simplified assumptions considering a 50% load and it may be noted that the emissions would vary with the engine or boiler load, air-fuel ratio, etc. The waste heat from the engines was assumed to be 20% of the engine output [7], while the heat pump is operated using an auxiliary engine thereby reducing the heat required from the heat pump and the peak power of the heat pump.

Table 2: Parameters and cost of the components considered in the study

	Efficiency	*Specific CAPEX*	*O&M cost*	*Refs*
Auxilary engine	35% [a]	350€/kW	2 %	[8,20]
Oil-boiler	90%	100€/kW	2 %	[21]
Heat pump	3.5 [b]	750€/kW	1 %	[21,22]

[a] assumed, [b] coefficient of performance

For manufacturing and end-of-life of components, the power rating of the component determines the size of the components (see Table 1). A heat pump with a lower power capacity is assumed for scenario 2 (calculated to be 90%) than for scenario 1 as the excess heat from the auxiliary engine is also used. The material composition of the heat pump and boiler for inventory analysis is assumed from the study by Miralles et al. [23]. It is assumed that additional auxiliary engine capacity is not required considering that the installed capacity that is used during navigation through the sea may be used at ports for supplying electricity to the heat pump. Since additional capacity is not assumed, the engine construction is not included in the assessment.

The total life cycle impact assessment (LCA) for global warming potential (GWP) (kCO_2eq/year) is calculated by combining the environmental impact from upstream (IA_{WTT} (kgCO_2eq per MJ_{fuel})), downstream (IA_{TTW} (kgCO_2eq per MJ_{fuel})), manufacturing with end-of-life recycling ($IA_{man,eol}$ (kgCO_2eq per kW)) phases as shown in Equation 1. In addition, the emission of SO_x and NO_x are calculated for each option but not converted to a midpoint indicator such as acidification or eutrophication.

$$LCA = IA_{WTT} \times f_c + IA_{TTW,c} \times f_c + \frac{P_C \times IA_{man,eol}}{t} \quad (1)$$

where f_c is the annual fuel consumption in MJ, P_C is the capacity of the heat pump or boiler for each scenario (kW) *and t* is the service life of the engine, boiler, and heat pump which is assumed to be 25 years.

2.4 Economic assessment

The economic assessment is performed using the total cost of ownership (TCO) method based on the system boundaries in line with the LCA as shown in Fig. 2. In addition, the cost is calculated for the functional unit 'the annual thermal energy required for the ship while at port'. Three costs are considered: 1) operation cost related to the fuel or electricity use, ii) capital cost related to the cost of equipment, and iii) maintenance cost. The cost for components and maintenance costs are also shown in Table 2. The operational cost considered here is the cost of the fuel or electricity required for the operation, represented by C_F (€/MJ). Capital cost is the cost of capital equipment (heat pump or oil boiler) represented by E_C (€/kW) and the capital cost is converted to the net present value where the future cost is discounted to the present value using the capital recovery factor (*crf*) given in Equation 2, where *t* is the service life of the components, and *i* is the discount rate (5%).

$$crf = \frac{i\,(1+i)^t}{(1+i)^t - 1} \quad (2)$$

The annual maintenance cost is considered based on the capacity of the capital equipment (C_M) (€/kW/year). The total cost of ownership (TCO) (€/year) is the sum of all costs converted into annual costs as given in Equation 3.

$$TCO = C_F \times f_c + E_C \times P_C \times crf + C_M \times P_C \quad (3)$$

The following costs are considered for the fuel costs, for electricity (including the power tariff) 100€/MWh, for MGO 700 €/t, and for electro-methanol 1870 €/t [8].

2.5 Uncertainty and sensitivity analysis

The COP of the heat pump is sensitive to the sink and source temperatures which depend on the placement of the heat pump. For instance, a higher COP can be achieved if heat pumps can reuse low-temperature engine cooling water, which is normally discharged into the sea [11]. Hence, we include a range of possible outcomes in the analysis by considering COP values between 3 and 4 and included these uncertainty levels in the result. The influence of the EU ETS as a policy for individual scenarios is included in the sensitivity analysis. In the analysis, the price of the emission allowances varied between zero and 300 €/tCO_2. The analysis is performed individually for all scenarios as the policy applies to all configurations but will have an impact only on scenarios where marine gas oil is used. This can be considered similar to a carbon tax on fossil emissions from ships.

3. RESULT

3.1 Energy efficiency

The energy consumption results for the different scenarios are shown in Table 3 for both case study vessels. Significant savings in the energy required for different scenarios are observed. In S1, where the thermal load is supplied by a heat pump supplied with onshore port power, the energy required is 78% less than in S3a and S3b when the thermal load is supplied from an oil boiler. In S2a and S2b where the heat pump needs to be operated using electricity generated from the auxiliary engine the energy required is 31% less than that in scenarios where the thermal load is supplied from an oil boiler (S3a and S3b). The results show that installing a heat pump can reduce the energy use of the ship even if electricity has to be generated onboard using auxiliary engines. These case study vessels are already connected to the OSP, but installing a heat pump for other passenger ships that are not connected to the OSP is also beneficial from an energy use perspective.

Table 3: Energy consumption for different scenarios

	S1	*S2a & S2b*	*S3a & S3b*
Case study vessel 1			
Electricity from port (GJ)	3900	-	-
MGO required (GJ)	-	12000	17350
Case study vessel 2			
Electricity from port (GJ)	7200	-	-
MGO required (GJ)	-	22200	32000
% Energy saved compared to boiler	***78%***	***31%***	-

3.2 Emission results

The GHG emissions for all five scenarios are assessed from cradle to grave for the thermal load of the case study ships while moored at port. Fig. 3 shows the GWP results for the different scenarios accessed for the first case study vessel. The results show that GHG emissions can be significantly reduced when a heat pump connected to the OSP is used for the thermal load (S1). There is an 87% reduction in GHG emissions compared to the boiler powered by MGO. In S2a, when the heat pump operates using electricity from auxiliary engines run on MGO, the GHG emission reduction is approximately 38% compared to the case with MGO and an oil-fired boiler (S3a).

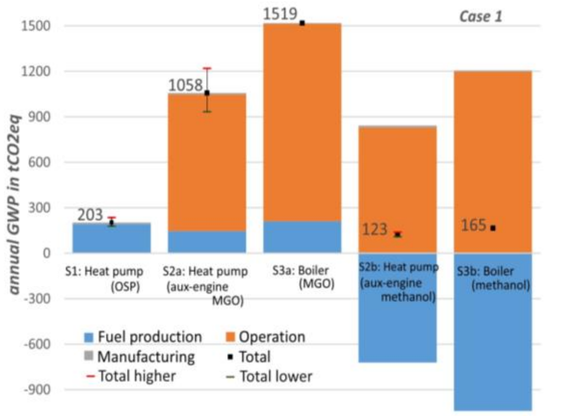

Figure 3: GWP of different scenarios for the first case study vessel. Total higher is total GHG emission considering heat pump COP 3 and lower is for COP 4.

Using electro-methanol in the boiler as in S3b and electro-methanol in the engine to power the heat pump as in S2b can have lower life cycle GHG emissions than a scenario where the heat pump is connected to an OSP (S1). This reduction is due to the assumption that the electro-fuel is produced from renewable electricity, whereas while using OSP about half of the electricity is considered from the electricity mix of Germany (GHG intensity of electricity mix is high). This scenario will be different in the future when more renewable energy is available in ports.

Fig. 4 shows the GWP for the different scenarios for the second case study vessel. The result is similar to the first case study with 87% GHG emission reduction for the S1 and 38% emission reduction in S2a compared to scenario S3a. In both cases, it can be noted that the impact of the manufacturing of the component is negligible for both the heat pump and the boiler. While using MGO and electro-methanol the emissions are primarily during the operation phase and for S1 there are no emissions during operation.

Apart from the GHG emission reduction that can be obtained using the heat pump, there are reductions in NO_x and SO_x emissions. For the first case study vessel, there is an emission reduction of 860 kg of SO_x and 900 kg of NO_x for S1 and an emission reduction of 330 kg of SO_x and 340 kg of NO_x for S2a. Because electro-methanol has no sulfur in the fuel, there will not be any significant SO_x emission in scenarios with electro-fuel. For electrofuel scenarios (S3a and S3b), NO_x emissions are not evaluated in the study.

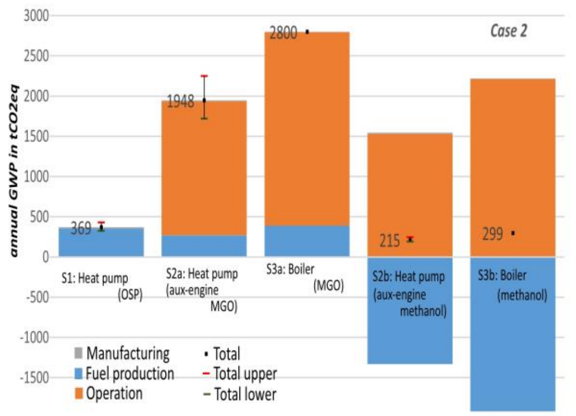

Figure 4: GWP of different scenarios for the second case study vessel. Total upper is total GHG emission considering heat pump COP 3 and lower is for COP 4.

The results on varying the COP of heat pumps are also shown in Fig. 3 and Fig. 4. Reduction of COP from 3.5 to 3 increases the emission by 16% for S1a and by 15% for S2a for both vessels. Increasing COP from 3.5 to 4 decreases the emission by 12% for S1a and S2a for both vessels. The results show that the detailed design of the heat pump system for optimizing the COP can affect the emission reduction potential.

3.3 Cost results

In this section, the results from the TCO for both case studies with different scenarios are analyzed. Fig. 5 shows the TCO for different scenarios accessed for the first case study vessel. The results show that S1 (heat pump with OSP) and S2a (heat pump with auxiliary electricity fueled by MGO) are more expensive than MGO-fired boiler. However, compared to the electro-methanol cases (S2b and S3b) S1 has a significantly lower cost. This shows that comparing the cost associated with GHG reduction, heat pumps connected to OSP have better prospects than other options such as switching to electro-fuels. It may be noted that the cost associated with EU ETS is not included in the result, and the effect of the EU ETS can make heat pumps more competitive which is detailed in section 3.4. The main cost associated with the heat pump is the cost of investment whereas it is the cost of fuel for the boiler option. With a higher cost of fuel as in S2b and S3b, the heat pump connected to the auxiliary engine has a considerable advantage over the boiler due to its higher overall efficiency.

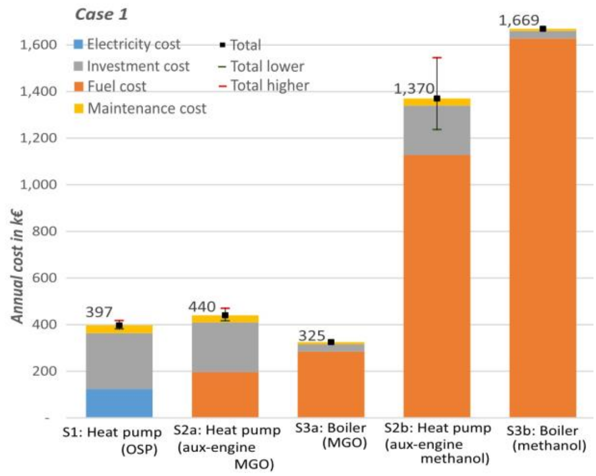

Figure 5: TCO of different scenarios for the first case study vessel. The higher represents the total cost considering heat pump COP 3 and the lower is for COP 4.

Fig. 6 shows the TCO for different scenarios accessed for the second case study vessel. For the second case study vessel, scenario 1 (the heat pump with OSP) has a similar cost to that of the MGO-fired boiler and has lower TCO when the COP of the heat pump is assumed to be 4. The difference in the results between the case studies highlights that the investment decision differs depending on the ship under consideration. With ships having a higher thermal demand (as in case 2), heat pumps would be competitive even without an incentive. This is because the higher investment cost is covered by decreased energy use (due to higher efficiency).

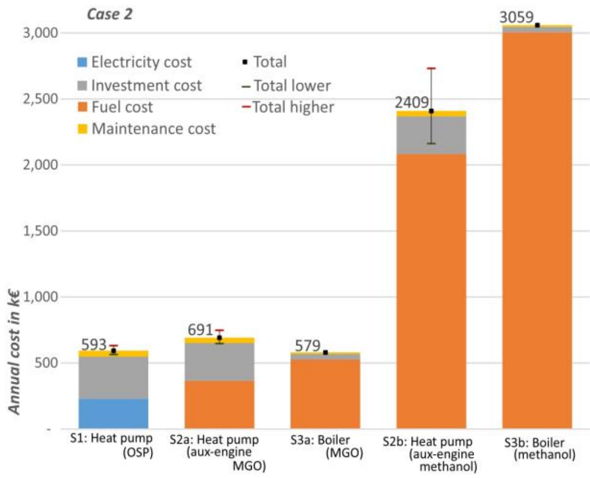

Figure 6: TCO of different scenarios for the second case study vessel. The higher represents the total cost considering heat pump COP 3 and the lower is for COP 4.

The uncertainties in the TCO results on different COPs of heat pumps are also shown in Fig. 5 and Fig. 6. A reduction in COP from 3.5 to 3 increases the TCO by 6% for S1a and by 8% for S2a for both vessels. Increasing the COP from 3.5 to 4 decreases the TCO by 5% for S1a and 6% for S2a for both vessels. The variation is lower compared with GHG emissions as the major cost associated with the heat pump is the investment cost.

3.4 Sensitivity analysis

In this section, TCOs are accessed for different carbon emission allowance prices if the EU ETS is introduced in the shipping industry. Fig. 7 shows the sensitivity analysis for different scenarios accessed for the first case study vessel. The results show that at the present allowance price level (about 90€/tCO_2), the heat pump connected to the OSP (S1) has significant cost benefits compared to S3a with an MGO-powered boiler. The return on investment calculation shows that with an allowance price of 90€/tCO_2, the payback period is six years. This indicates that retrofitting case study vessel 1 is economically desirable if ETS is introduced.

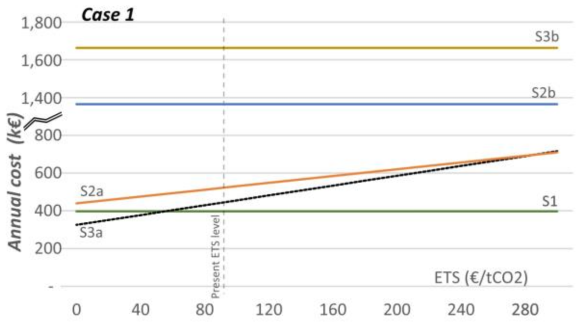

Figure 7:Sensitivity of TCO with different ETS prices for the first case study vessel

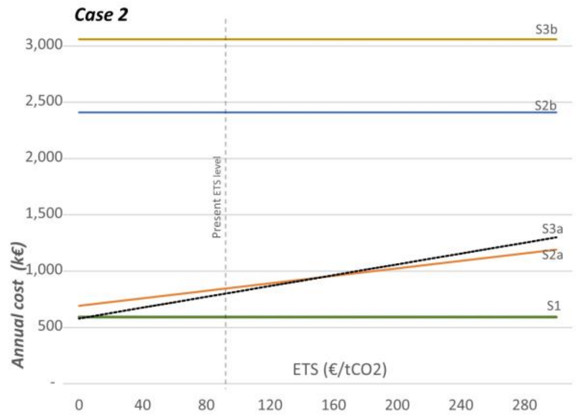

Figure 8: Sensitivity of TCO with different ETC prices for the second case study vessel

Fig. 8 shows a similar sensitivity analysis for the second case study vessel. For the second case study vessel already S1 has a TCO similar to that of base case S3a. Sensitivity analysis results show that S2a when the heat pump is operated using the auxiliary electricity also will be cost-competitive if ETS is considered. The return on investment calculation shows that heat pumps powered by OSP have a payback period of only 2.5 years with the present rate of ETS.

4. DISCUSSION

Similar to other sectors, such as industry, commercial, and residential sectors, the shipping sector especially the passenger segment can make use of heat pumps for decarbonization efforts to meet the heating demand. The utilization of heat pumps is mostly limited to the time at the port when the OSP is available due to the excess heat available from the engines in the shipping sector. The study accessed the possibility of using the heat pump directly from the OSP and using auxiliary generation sets from the energy, economic, and environmental perspectives.

Replacing oil boilers with heat pumps powered by OSP has multiple benefits from energy efficiency to the reduction of emissions such as GHGs, SO_x, NO_x, etc. This is particularly important for passenger ships as in the case study vessels as the ship operates the boiler in the port where air quality is a major concern [24]. There are also some emission reductions and fuel savings even if the electricity required for the heat pump is produced using auxiliary engines instead of being connected to the OSP. The life cycle result for the heat pump operated from OSP also shows a significant global warming potential reduction compared to oil-fired boilers, even considering the present electricity mix. With more renewables in the electricity mix available in the ports, these benefits would be even higher. The result also shows that the impact of the component production is negligible compared to the upstream (fuel production) and downstream (operation) emissions.

The total cost of ownership results show that cost competitiveness varies with the case study vessel parameters. However, the proposed regulations such as EU ETS can make a significant difference in the cost competitiveness of the heat pump system compared to the MGO boilers. The results show that for the second case study vessels can have a return on investment in less than three years if the price of carbon allowances in ETS is above 90€/tCO_2eq. The major cost item in the TCO is the investment cost of the heat pump, policies that support investment in heat pumps can also be beneficial. In addition, the investment cost is for the total capacity to be installed onboard, and support systems such as thermal energy storage can reduce the capacity of the heat pump by avoiding peak demands. Combining such measures can further reduce investment and operating costs. However, this aspect was not assessed in the present study.

One of the major limitations of this study is that the complete operation profile of the case study vessels including variations in the season, was not considered. The study could have included an uncertainty analysis of the cost of the fuel and investment cost for these options as well as the size requirement of the components onboard. This study is restricted to a preliminary analysis, and a detailed analysis may be performed in future studies considering the above aspects. Other benefits such as the possibility of using heat pumps reversibly during summer for cooling, easier and safer operation of heat pump, and increasing efficiency further by utilizing the low-temperature heat from the engine could also be investigated in future studies.

5. CONCLUSION

This study provides a preliminary comparison of the economic and environmental implications of installing heat pumps on two passenger vessels. In terms of thermal load alone, the heat pump has a GWP that is 87 percent lower than that of an oil-fired boiler. In addition, switching to a heat pump eliminates the NO_x, and SO_x emissions, which have a negative impact on the air quality in the populated areas near the port. When connected to onshore power, the heat pump has a higher total cost of ownership without the emission trading scheme for the first case study vessel and less for the second case study ship. With the emission trading scheme, heat pumps are cost-effective for both case study vessels, and have a lower cost of ownership compared to using electro-fuel in a boiler. In summary, the replacement of a boiler with a heat pump is found to be an effective emission reduction measure for ships using onshore power, but the study observed that the payback period will vary depending on the vessel's energy needs and price level for emission allowances.

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APPENDIX A

A.1 Nomenclature

C_F	Cost of the fuel	(€/MJ)
E_C	Capital cost	(€/kW)
crf	Capital recovery factor	
i	Discounting rate	(%)
t	Service life	(years)
C_M	Maintenance cost	(€/kW/year)
TCO	Total cost of ownership	(€/year)
P_C	Heat pump or boiler capacity	(kW)
f_c	Annual fuel consumption	(MJ)
GWP	Global warming potential	(kgCO_2eq)
IA	Impact assement result	

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