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Organic Rankine cycle-based waste heat recovery system combined with thermal energy storage for emission-free power generation on ships during harbor stays

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Abstract

The pollutant emissions from ships in harbor are a pressing concern due to their direct impact on the health of the population. The use of electric-battery propulsion is a viable solution to reduce the emissions in coastal areas, but it is only applicable to small ferries. Large cruise ships commonly utilize shore power connection to provide onboard electricity, avoiding pollution during harbor stays. However, this solution is not applicable during short stays. This paper presents a novel and energy-efficient way to supply zero-emission power during harbor stays of marine vessels. The proposed system combines the use of a thermal energy storage and a waste heat recovery system based on the organic Rankine cycle technology. The objective of this work is to investigate the technical feasibility of the proposed system and to compare its cost-effectiveness with the alternative solution of using
batteries during harbor stays. The study is based on a case study of a hypothetical ferry requiring 1 MW of auxiliary power during harbor stays. The results suggest that the proposed system would require the installation of a storage tank of around 82 m³, and that it could be economically competitive with the battery-based solution, especially when considering its installation on newly built ships. Lastly, it is estimated that the installation of the proposed concept would lead to reduction of the ferry’s carbon dioxide emissions by 8 %.

Keywords: organic Rankine cycle, ferry, zero-emission, waste heat recovery, thermal energy storage, battery system

1. Introduction

Although most of the emissions from shipping take place at sea, those released in harbor areas and port cities are the most noticeable for humans. A previous study by Heller et al. [1] suggested that the Long Beach communities located near the harbor of Los Angeles experienced 2.9 % higher rates of asthma, depression and coronary heart disease compared to the other communities of the area. Moreover, the California Resources Board attributed 3,700 yearly premature deaths to harbors and the shipment of goods [2]. Globally, shipping-related particulate matter emissions are estimated to be the cause of approximately 60,000 cardiopulmonary and lung cancer deaths annually, with the coasts of Europe, East and South Asia being the most affected areas [3]. In addition, a study from Merk [4] concluded that between 70 % and 100 % of emissions in harbors in developed countries can be attributed to shipping, while emissions from trucks and equipment account for up to 20 % and 15 %, respectively.

As a way to promote a reduction of the emission of pollutants in port areas, several incentive schemes were introduced in recent years. These incentive programs encourage ships calling in the various ports to reduce their emission levels below the requirements of the IMO and normally reward them with a discount on port dues [5]. The Environmental Ship Index (ESI) and the Clean Shipping Index (CSI) are among the most commonly applied incentive schemes.
Ports can also participate in multiple schemes; for example, the port of Vancouver recognizes an EcoAction Program [6] under which green ships can attain a reduction on port dues in the range from 23 % to 47 %. Lastly, individual incentive schemes were also introduced by single ports as a way to support green shipping; the harbor of Sandefjord in Norway, for example, rewards cleaner ferries by awarding them with the best departure times. Ship-owners are therefore facing an increasing demand for greener shipping, which is supported by significant economic benefits.

One of the most promising approaches to reduce the environmental impact of a ship is to utilize the waste heat released by its engine. This waste heat can be recovered to generate power, heating and cooling [7,8]. The use of organic Rankine cycle (ORC) power systems is one of the most attractive solutions to convert the main engine waste heat into power [9].

The use of WHR systems, utilizing the waste heat released by a ship’s main engine for the production of power or heating, leads to a reduction of the emissions during the ship’s sailing phases. During the harbor stays, neither the ship’s main engine nor the WHR unit are operated, and therefore the implementation of such systems does not result in a reduction of the pollutant emissions in harbor areas.

A technical solution to operate WHR systems also during harbor stays is the use of thermal energy storage (TES) systems. TES systems make it possible to store the waste heat released by the ship’s main engine, and to use it when required on board. In this context, Baldi et al. [10] investigated the use of water-based TES systems on board merchant ships and found that the installation of a 1000 m³ TES would enable reducing the consumption of the auxiliary boilers by 90 %. Ancona et al. [11] proposed an optimization framework to minimize the fuel consumption of a vessel by optimizing the load of the ship energy system. The results of their investigations suggested that the use of a thermal energy system, in combination with an optimal load allocation of the ship energy system, would result in a reduction of the fuel consumption by around 14 %. Lastly, Fridolfsson [12] investigated the use of heat storage units as part of a ship WHR system and found that the use of phase-change material-based TES systems would result in the reduction of the required volume for the TES by around 50 %.
The abovementioned work from Ancona et al. [11] suggested that the use of TES systems on board ships could eliminate the use of auxiliary boilers during harbor stays. However, current TES systems, because they focus on the heat needs on board, are not capable of eliminating the emissions for propulsion when approaching the harbor, nor those of the auxiliary generators supplying the electricity required on board while the ship is in the harbor (i.e. the electricity requirements for the restaurants in cruises/ferries).

An attractive solution to eliminate completely the emissions in harbor areas is the use of electric propulsion [13]. Many studies are investigating the prospects of developing zero-emission electric-powered ships for public transportation [14]. This solution is, however, applicable only for small ferries and short-sea shipping [15], because the investment cost and space requirements for the battery system increase substantially for ships with higher energy demands.

Nonetheless, specific actions are being taken also to limit emissions in harbor areas by larger ships. For example, an increasing number of ports is offering onshore power supply [16] for seagoing ships, allowing them to shut off auxiliary generators during harbor stays. In addition, the use of battery systems to supply auxiliary power in port areas is under investigation for ferries, whose time-limited harbor stays make it infeasible to connect with the shore power infrastructure. In this case, batteries are charged during voyage, either by using the main engine shaft power or by using a WHR system, and are used during harbor stays to supply the required power on board.

Considering this solution, batteries can be used also for larger ships, because the onboard power requirements during harbor stays are low compared to the propulsion power, and the harbor stays are generally short compared to the sailing time. This solution presents, however, a series of downsides: i) the battery system is large and expensive; ii) the system needs to be replaced multiple times throughout the life-time of the ferry (due to the limited life-time of the batteries); and iii) this solution does not result in an overall reduction of the pollutant emissions, but rather in a shift of the location where the pollutants are emitted (except for the case where the battery system is charged by a WHR system or renewable resources). These drawbacks apply regardless of the size of the ship.
This paper investigates the technical and economic feasibility of a novel and energy-efficient way to supply zero-emission power during harbor stays for ferries. The proposed system combines the use of TES and a WHR system based on the ORC technology and is applicable also to other ship types anchoring in ports where shore power connection is not available. The TES is charged during the voyage by using the waste heat available from the main engine, and is then utilized to drive an ORC unit during harbor stays. The ORC unit supplies all the onboard energy demand during the harbor stays and, therefore, the ship does not produce any emission while anchoring at port. The concept has two main advantages compared to the battery solution: i) it has a longer expected life-time and therefore it does not need to be replaced over time (the ORC unit can have a life-time of over 20 years), and ii) it results in an overall reduction of the ship emissions, because the power produced by the ORC unit is attained by harvesting the waste heat from the main engine.

The evaluations are based on a case study of a hypothetical ferry requiring 1 MW of auxiliary power during harbor stays, whose sailing profile was provided by Fjord Line. Two types of TES were considered, the use of a stratified tank and of a two-tank system.

By proposing and evaluating a novel concept to supply zero-emission power during harbor stays for ferries, this work provides a solid contribution to the state-of-the-art. In particular, the two main novel aspects of the work are the following: i) considering the use of WHR power generation during harbor stays, while previous works investigating heat-to-power WHR systems for maritime applications were limited to consider the production of electricity during sailing [9]; and ii) considering the use of a TES system for electricity generation on ships, contrary to previous works where the inclusion of TES systems on ships was limited to the coverage of only the onboard heating demand [10–12]. In addition, the comparison of the use of stratified and two-tank storage solutions in terms of energy efficiency, volume requirements, and economic attractiveness on board a vessel is a novel contribution to state-of-the-art. The findings of the work support both researchers and industry in the development of novel solutions to reduce the environmental impact of ships during harbor stays.

The paper is structured as follows: Section 2 explains the applied methods. Section 3 presents the results. The results are discussed in Section 4, and the conclusions are outlined in Section 5.
2. Methods

2.1. Concept, case study and engine performance data

This paper evaluates the prospects of supplying the energy required on board a ferry during harbor stays by utilizing a system comprising an ORC unit and a TES. Figure 1 shows the layout of the proposed concept.

![Figure 1. Sketch of the proposed concept. The dashed line represents the oil loop, while the dotted line indicates the ORC loop.](image)

During sailing, the exhaust gases are utilized to heat up a thermal oil, which is partly stored in the TES and partly utilized to run the ORC unit. During harbor stays, the TES is discharged in order to run the ORC unit. In defining the control strategy for the system, the first priority is to ensure the availability of the required power during the harbor stays. Auxiliary generators are utilized during sailing to provide the power demand that cannot be satisfied by the ORC unit. Both a stratified storage tank and a two-tank system were considered as TES. The stratified tank operates according to the stratification process, which occurs due to the variation of a fluid’s density as a function of its temperature. This enables having both a hot and a cold zone in the same container. In the two-tank solution, the hot and cold fluids are physically separated. Therminol 66 was selected as the thermal oil, because of its capability to operate up to 345 °C without being pressurized [17].

The study is based on a case study of a hypothetical ferry powered by liquefied natural gas (LNG). The information about the ferry machinery system, sailing profile and energy requirements were
provided by Fjord Line, ensuring a realistic case study. The ship propulsion system featured two propeller lines, each one powered by an 8 MW Wärtsilä 7L46DF engine. The engine performance data at 75 % and 100 % load were acquired through the manufacturer’s product guide [18], while the engine performance at intermediate points was estimated using linear interpolation among the data points given in the product guide.

As shown in Table 1, the sailing profile of the ferry is characterized by the following phases: i) harbor stays with connection to the shore power; ii) harbor stays without connection to the shore power; iii) sailing at low load (maneuvering); and iv) sailing at high load.

According to the information provided by Fjord Line, it was assumed that the cruise ship required 1 MW of power for onboard services (e.g. for supplying the restaurants on board and for heating purposes) throughout the whole sailing profile. Because no information about the exhaust gases was available for the engine loads below 75 %, it was assumed that no heat could be harvested from the exhaust gases during the sailing phases at low engine loads (the ORC power production was therefore set to zero during these phases). This assumption leads to the attainment of conservative results. In addition, it was assumed that the ferry was operated all year round according to the specified sailing profile.

The following subsections describe the models that were used to describe the performance of the ORC unit, the waste heat recovery boiler and the TES systems. All the models were developed using Matlab 2016a [19]. The approaches used to optimize the overall system and to estimate its economic performance are detailed in Sections 2.5 and 2.6, respectively.

Table 1. Description of the considered sailing profile.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Sailing mode</th>
<th>Engine load [%]</th>
<th>Duration [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Maneuvering</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>Harbor stay</td>
<td>0</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>Sailing</td>
<td>85</td>
<td>150</td>
</tr>
<tr>
<td>4</td>
<td>Harbor stay</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>Sailing</td>
<td>85</td>
<td>150</td>
</tr>
<tr>
<td>6</td>
<td>Harbor stay</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>7</td>
<td>Sailing</td>
<td>85</td>
<td>150</td>
</tr>
<tr>
<td>8</td>
<td>Harbor stay</td>
<td>0</td>
<td>40</td>
</tr>
</tbody>
</table>
2.2. **Organic Rankine cycle model**

This study considered the installation of a simple, non-recuperated ORC unit, whose design performance was computed with the numerical model previously described in Andreasen et al. [20]. The heat exchangers (boiler and condenser) were modelled with a minimum pinch point approach (the minimum temperature difference between the hot and cold streams) and fixed isentropic efficiencies were assumed for the pump and the expander (see Table S2 in the supplementary material). The impact of the pressure losses in the various heat exchangers was neglected, and the ORC net power output ($\dot{W}_{\text{Net}}$) was computed as follows:

$$\dot{W}_{\text{Net}} = \dot{W}_{\text{exp}} \eta_{\text{gear}} \eta_{\text{gen}} - \dot{W}_{\text{pump}} - \dot{W}_{\text{pump,sw}}$$  \hspace{1cm} (1)

where $\eta_{\text{gear}}$ and $\eta_{\text{gen}}$ are the efficiencies of the gearbox and the electrical generator. The subscripts exp and sw stand for expander and seawater, respectively. The ORC optimization procedure was set up to minimize the required oil flow rate required to attain the target power output (1 MW). The optimization variables were the working fluid mass flow rate, the pressures in the condenser and evaporator, and the superheating degree at the turbine inlet. The simulations were carried out considering cyclopentane as the working fluid, because it has previously been proven to be a suitable candidate for waste heat recovery applications in the considered temperature range [21,22]. The thermo-physical properties of cyclopentane were retrieved from Coolprop 4.2.5 [23].

The performance of the ORC unit during off-design operation was estimated using a steady-state off-design performance model presented in ref. [24]. Additional information regarding the ORC off-design modeling is included in section S1 in the supplementary material.

2.3. **Exhaust recovery heat exchanger**
The exhaust recovery heat exchanger uses the heat from the exhaust gases to heat up the thermal oil to the defined temperature. As a way to avoid the need to mix the exhaust flows from the two available engines, it was assumed that two identical exhaust recovery heat exchangers were required in order to realize the proposed concept. A finned tube heat exchanger was selected, because this technology is commonly utilized in the maritime industry for WHR applications. The design of the exhaust recovery heat exchanger was carried out using a thermodynamic model described in Baldasso et al. [24]. Additional information regarding the exhaust recovery heat exchanger design procedure is reported in section S2 in the supplementary material.

The volume of the heat exchanger was estimated as follows [25]:

\[
V_{\text{WHR,hex}} = l_t \cdot P_l \cdot P_t \cdot (N_{\text{tp}} + 1)(N_{\text{tr}} + 1)
\]

where \( l_t \), \( P_l \), and \( P_t \) represent the length of the heat exchanger tubes, and the longitudinal and the transversal pitch, respectively. The number of tube passes and the number of tube rows are denoted by \( N_{\text{tp}} \) and \( N_{\text{tr}} \).

2.4. Thermal energy storage models

The behavior of the stratified tank, which was considered to have a cylindrical shape and a volume \( V_{\text{tank}} \), was estimated by means of a 1D model. The tank was described as the sum of \( N \) horizontal slices (layers) of equal height, each behaving as a fully mixed tank.

For the case of the two-tank system, both thermal storage units were modelled as fully mixed and were assumed to have the same dimensions and insulation levels. Additional information regarding the models of the stratified tank and two-tank systems is reported in sections S3 and S4 in the supplementary material.

2.5. Overall system optimization

The overall optimization of the system comprising the ORC unit and the TES was carried out following the procedure illustrated in Figure 2. The ORC unit design was carried out to minimize the required oil flow to produce the target power output. This ensured the minimization of the volume of
the TES. A sensitivity analysis was carried out with respect to the oil maximum temperature, considering the range between 260 °C and 340 °C. The maximum considered oil temperature was 340 °C to avoid the need to have a pressurized TES.

The exhaust recovery heat exchanger design was carried out by means of a two-step procedure. First, the maximum flow rate of oil that could be produced given the boundary conditions of the system was estimated (inlet and outlet temperatures of the thermal oil, exhaust characteristics, and design constraints on the heat exchanger). Second, an optimization procedure was carried out to identify the boiler design leading to the minimum space requirement and a production of thermal oil equal to at least 95 % the flow rate computed at the previous step. After carrying out a sensitivity analysis on this parameter, it was decided to carry out a volume minimization procedure and to select the flow rate threshold of 95 % of the maximum attainable flow. The results of this sensitivity analysis are presented in the results section.

The optimization of the ORC unit and of the exhaust recovery heat exchanger was not carried out simultaneously because the results of the ORC optimization defined the thermal oil inlet temperature in the recovery heat exchanger, and therefore splitting the two optimizations reduces the computational effort.

The optimization procedures were carried out by a combination of particle swarm and pattern search optimizers available in Matlab 2016a [19]. Given the heuristic nature of the optimization algorithm, the optimizations were carried out multiple times to ensure having reached the global optima. The particle swarm optimizer was run for 50 generations with a swarm size of 1,000 individuals for the ORC design optimization phase, and for 100 generations with a swarm size of 2,000 individuals for the OTB design optimization routine. In both cases, the pattern search optimization routine was executed for 500 iterations.
Figure 2. Sketch of the overall optimization procedure. The ORC and heat exchanger optimization routines are highlighted by the dashed boxes, while the list of the fixed parameters and the optimization variables is available in Tables S2 and S3 in the supplementary material.

Off-design performance maps were generated to describe the off-design performance of both the ORC unit and the recovery heat exchanger. The tank was dimensioned to supply the heat required by the ORC during the harbour stays. Given an initial guess value, the tank size was progressively increased by means of an oversizing factor. The tank oversizing factor was initially set to 1%, and it was then increased (by increments of 1%) until harbor coverage was reached.

When carrying out the sailing simulation, the control strategy was set up to predict, at the beginning of each sailing phase, the amount of thermal oil at high temperature to be stored in the tank that would enable the production of the required power during the following harbor stay. Given the duration of the sailing phase and the flow rate of oil that could be produced in the recovery heat exchanger, the oil
flow rate was accordingly supplied to the tank and the ORC unit (in case the production exceeded the requirements of the storage tank).

In the stratified storage configuration, the temperature of the discharged thermal oil decreases during the harbor stay, and therefore the oil discharge flow rate was progressively increased to maintain a constant power production from the ORC unit. Centrifugal pumps are commonly characterized by a preferred operating flow rate between 70 % and 120 % of the best efficiency point [26]. It was assumed that the pump was operated in design point at 70 % of the best efficiency point flow, and therefore the tank cut-off temperature was selected so that the oil flow rate did not exceed 170 % the nominal flow.

Three days of operation were simulated, ensuring that the system can be operated cyclically. For the stratified tank case, 5 % of the tank height was assumed to be subjected to mixing, and the initial temperature distribution was attained by means of three charging/discharging cycles. The impact of the assumed value for the mixing section was quantified by a sensitivity analysis.

The lists of fixed parameters and optimization variables used for the overall calculation procedure are available in the supplementary material, in Tables S2 and S3, respectively. The performance of the ORC system was quantified by an energy coverage factor:

\[
\text{Energy coverage} \, [\%] = \frac{\text{Annual energy supplied by ORC}}{\text{Annual energy required on board}} \tag{3}
\]

Lastly, the reduction of carbon dioxide (CO), CO\(_2\), sulphur dioxide (SO\(_2\)), and NO\(_x\) emissions attainable by installing the proposed system were computed using emission factors of 1.3 g/kWh, 445 g/kWh, 0.24 g/kWh and 2.4 g/kWh, respectively. The emission factors were retrieved from Kristensen [27], assuming the use of four-stroke dual fuel engines with 1 % sulphur content in the pilot fuel oil.

The attainable daily emission reductions were computed based on the amount of energy that is produced by the ORC unit instead of the auxiliary generators. This can be calculated by multiplying the daily onboard energy requirement of 14.667 MWh (computed by multiplying the required power
on board, 1 MW, by the amount of time when the cruise is not connected to the shore power) by the energy coverage factor (see Equation 18). The emission reductions were attained by multiplying the emission reduction factors by the amount of energy that is produced by the ORC unit instead of the auxiliary generators. Lastly, the relative reduction in the CO2 emissions was calculated by comparing the CO2 emission reductions with the overall CO2 emissions from the ferry. These were attained by multiplying the CO2 emission factor by the daily energy requirements for propulsion (137 MWh) and onboard use (14.667 MWh).

2.6. Economic investigations

The economic performance of the proposed concept was evaluated by comparing it to the use of lithium batteries. The comparison was based on the LCOE to supply the auxiliary power on board. All the economic figures are expressed in US dollars. The LCOE ($/kWh) is defined as [28]:

\[
LCOE = \frac{I_0 + \sum_{y=1}^{n} \frac{I_y + O&M_y + F_y}{(1 + r)^y}}{\sum_{y=1}^{n} \frac{E_y}{(1 + r)^y}}
\]

where the calculation considers that the system is operated for a number of years equal to \(n\). The symbols \(I_y, O&M_y, F_y\) and \(E_y\) represent the investment cost, operation and maintenance costs, fuel expenditures, and the electricity generation at the year \(y\). The symbol \(r\) is the discount rate considered for depreciation, assumed to be of 6 % [9], while \(I_0\) represents the initial investment cost. The electricity generation represents the annual energy requirement of the cruise for onboard use, while the fuel expenditures are equal to the price of the LNG required to run the auxiliary generators. The consumption of the LNG generators was assumed to be 160 g/kWh [27]. The procedure used to estimate the cost of the various components of the system is presented in section S5 in the supplementary material.

The LCOE calculation is subject to multiple uncertainty factors, mainly due to the cost estimates. Therefore, the impact of the uncertainty factors on the estimated LCOE was assessed by means of
local and global uncertainty analyses, the latter carried out using the Monte-Carlo method over 50 samples [29]. The list of the considered uncertainty factors and their ranges are shown in Table 2. The battery life-time was estimated considering a number of equivalent cycles between 5,000 and 10,000 [30] and a battery usage corresponding to four equivalent cycles per day. The batteries were assumed to have a discharge depth of 100 %. The impact of the battery life-time on the LCOE was estimated through a local sensitivity analysis, while the battery life-time was assumed to be five years in the other investigations.

The LCOE calculation was carried out assuming a life-time of the system between five and 25 years, to cover both retrofit solutions and the installation on a newly built ferry.

It was assumed that the ORC operational life was limited to the ship expected life-time. This means that the ORC value was set to zero at the end of the ship operational life, even for retrofit cases for which the ship life-time was lower than the ORC expected life-time (25 years).

Table 2. Uncertainty ranges of the parameters used in the LCOE calculation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lower bound</th>
<th>Upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ORC system</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TES and recovery heat exchanger cost</td>
<td>-30 %</td>
<td>+30 %</td>
</tr>
<tr>
<td>Thermal oil cost [$/kg]</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td><strong>Battery systems</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery system total cost [$/kWh]</td>
<td>600</td>
<td>900</td>
</tr>
<tr>
<td>Life-time [yr]</td>
<td>3</td>
<td>7</td>
</tr>
</tbody>
</table>

2.7. **Model validation**

All the models used in the present work were validated either against experimental data or other works published in literature. Details regarding the validation of the numerical models are presented in section S6 in the supplementary material.

3. **Results**

3.1. **Comparison of storage concepts**
Figure 3 depicts the impact of the selected thermal oil maximum temperature on the performance of the two proposed systems. The reader is referred to Tables S4 and S5 in the supplementary material for the optimized design variables for the ORC and exhaust recovery heat exchanger.

First, it may be noticed that a decrease in the maximum oil temperature results in an increase of the required storage volume. This is connected to the fact that lower oil temperatures lead to optimized ORC units with lower thermal efficiencies, and thus a higher flow of thermal oil is required to produce the selected target power output.

Second, the results indicate that when decreasing the oil temperature, the energy coverage increases, then reaches a maximum corresponding to an oil temperature of around 310 °C, and then decreases. This is due to the interaction between two phenomena. As mentioned before, the ORC unit requires higher flow rates when the oil temperature is lower. On the other hand, setting a lower value for the oil maximum temperature enables the generation of a higher mass flow of oil in the recovery heat exchangers, making it possible to increase the average load at which the ORC operates. Nonetheless, after a certain threshold, around 310 °C for the considered case, the increased availability of thermal oil does not counterbalance the lower ORC efficiency, and thus the energy coverage factor starts to decline.

The same trend appears when looking at the trend for the estimated LCOE of the system, which was calculated using a five- year time-span and by setting 3,000 $/kWh, 8 $/kg, and 12 $/mmBTU to the price of the ORC unit, of the thermal oil, and the LNG, respectively. The estimated LCOE decreases when decreasing the maximum oil temperature from 340 °C to 310 °C and then starts to increase. In this case, a decrease of the oil maximum temperature has a positive impact on the LCOE, because the increased cost of the storage tank is more than compensated by the increase in energy production by the ORC. However, when the decrease in oil temperature no longer results in increased energy production (oil temperatures below 310 °C), the LCOE starts to increase.
As shown in Figure 3b, the two tank alternatives are capable of supplying a similar amount of energy during the voyage. Nevertheless, the use of a stratified tank results in a storage volume corresponding to around 60 % of the volume required when having two separate tanks, which results also in lower estimated LCOEs (see Figure 3c). Looking at the energy coverage, namely, the share of onboard energy requirements that the ORC is able to supply, the maximum estimated values are 82.6 % and 82.1 %, for the two-tank and the thermocline cases, respectively. In both cases, the maximum energy productions were attained for the case where the oil was heated up to 310 °C. The corresponding volume requirements were of 142.2 m³ and 82.1 m³, for the two-tank and the stratified tank configuration, respectively. The volume required for the recovery heat exchangers is not affected by the technology selected for the storage tank and was estimated to be approximately 6.4 m³ (3.2 m² for each heat exchanger).

From the environmental point of view, both configurations lead to a daily reduction of the ferry emissions of CO, CO₂, SO₂ and NOₓ by around 15.8 kg, 5.4 ton, 2.9 kg, and 29.1 kg, respectively. On a relative basis, the installation of the proposed system leads to a reduction of the CO₂ emission by 8 %. This value is in accordance with the findings from Bouman et al. [31], which suggested that the use of WHR units on board vessels could lead to a reduction of the CO₂ emissions in the range from 1 % to 20 %.
Figure 4 shows the impact of constraining the oil flow generated in the exhaust recovery heat exchanger in a range between 80 % and 100 % of the maximum attainable value. Table S6 in the supplementary material presents the optimized exhaust recovery heat exchanger design variables as a function of the generated oil flow. Each point in the figure represents the performance of an optimized exhaust recovery heat exchanger, where the amount of produced oil was constrained in the selected range. The results of the sensitivity analysis on the flow reduction factor indicate that reducing the oil flow rate leads to an almost linear reduction of the energy contribution from the ORC unit. On the contrary, both the volume requirements for the oil heater and the estimated LCOE of the system tend to decrease sharply and converge to a constant value or to increase slowly when the oil flow rate is reduced. The plots suggest that the selected value of 95 % represents a good trade-off enabling a significant reduction of the oil heater volume requirements.

Figure 4. Impact of reducing the design flow rate of the exhaust gas recovery heat exchanger on a) the volume of the recovery heat exchanger; b) coverage of onboard energy demand; c) LCOE. The results are attained for the stratified tank configuration, considering a maximum oil temperature of 310 °C.

Figure 5 represents the daily ORC production profile for the two considered cases. The different power outputs produced by the ORC system during the first three sailing periods are due to the different durations of the subsequent harbor stays (60 minutes, 50 minutes and 40 minutes, respectively). The limited production in the fourth sailing period is explained by the fact that the tank needed to be completely filled to be used to produce energy during the first harbor stay of the
following day. The results indicate that both configurations are suitable for supplying the required power during the harbor stays and that small differences appear between the two considered tank solutions. This is confirmed by the similar energy productions, as shown in Figure 4b.

The sensitivity analysis on the impact of the mixing ratio on the performance of the thermocline storage solution indicates a low incidence of this parameter on the storage tank volume and on the energy coverage factor. Varying the mixing ratio between 2 % and 8 % resulted in relative variations of the volume of the energy storage, on the annual energy production and of the estimated LCOE within 1 %. In addition, a sensitivity analysis on the number of discretization layers used in the stratified tank model was performed, and the results indicate that increasing the number of discretization layers from 300 (the value used in the calculations) to 450 leads to a relative variation in the estimated energy coverage lower than 2 %.

![Graph showing ORC power production throughout the sailing route for both proposed configurations.](image)

**Figure 5.** ORC power production throughout the sailing route for both proposed configurations.

### 3.2. Economic assessment

The economic comparison between the proposed system and the battery configuration was carried out by considering the use of a thermocline storage and a maximum oil temperature of 310 °C; see Table 3. The values represent the mean of the distributions computed through the uncertainty analysis. The displayed investment cost refers to the cost for purchasing and installing the ORC/battery system.
When considering the battery system, the investment cost was included in the LCOE calculations in every year $y$, where the system had to be replaced due to its limited life-time.

The results indicate that the battery system results in a lower LCOE when considering a five-year scenario, while the ORC LCOE is 30% lower than the battery solution when a 20-year scenario is considered. The investment cost for the ORC system is roughly four times higher than the one of the battery system, while the annual expenditures (sum of fuel expenditures and maintenance costs) are lower for the ORC system ($84,800 compared to $472,880). Figure 6 depicts the cost breakdown of the ORC system. The ORC unit represents the highest share (64%), and it is followed by the exhaust recovery heat exchanger (21%), the thermal oil (10%) and the storage tank (5%).

Table 3. Results of the economic estimations for the battery and ORC systems. For the ORC system, a total cost of 3,000 $/kWh was assumed, while a life-time of five years was assumed for the battery system. The LNG price was set to 12 $/mmBTU.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Battery system</th>
<th>ORC system</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 years LCOE ($/kWh)</td>
<td>0.141</td>
<td>0.2291</td>
</tr>
<tr>
<td>20 years LCOE ($/kWh)</td>
<td>0.140</td>
<td>0.1022</td>
</tr>
<tr>
<td>Investment cost (k$)</td>
<td>1,125</td>
<td>4,523</td>
</tr>
<tr>
<td>Annual fuel expenditures (k$)</td>
<td>472.88</td>
<td>84.80</td>
</tr>
<tr>
<td>Annual maintenance cost (k$)</td>
<td>16.88</td>
<td>67.85</td>
</tr>
</tbody>
</table>

Figure 6. Cost breakdown for the ORC system.
Figure 7 depicts the results of the sensitivity analyses carried out for the estimated LCOEs. Figure 7a shows that the estimated LCOE for the ORC system is highly affected by the number of years for which the system is assumed to be operating. The longer the considered period, the lower the resulting LCOE. On the contrary, no variation is seen with respect to the battery system. This is because the battery system needs to be replaced every five years. Moreover, all the ORC solutions result in a lower LCOE than the battery system if a period of 15 or more years is considered. Figure 7b depicts the impact of the LNG price on the estimated 10-year LCOE. The plot shows that the battery system is the one which is most affected by this parameter, and that the ORC system is more promising when the LNG price is high. This results from the fact that the LNG price affects linearly the annual fuel expenditures, which are a predominant factor in defining the LCOE of the battery system. The ORC system requires, on the contrary, lower amounts of LNG (around 20% the amount required by the battery system), and therefore it is less affected by LNG price fluctuations.

Figure 8 shows the results of the local sensitivity analysis which was carried out for the uncertain parameters detailed in Table 5. The sensitivity analysis was carried out considering a life-time of 20 years, referring to the installation of the systems on a newly built ferry. The figure suggests that the variation of the uncertain parameters (except the battery life-time) results in a relative variation of the expected LCOE within 10%. The battery systems prove to be the most affected by uncertainty, with a variation of the expected LCOE by around 8% with a variation of the battery specific cost of ± 20%. Lastly, the impact of the estimated battery life-time is identified to have a significant impact on the economic results. A reduction of the estimated life-time from the baseline of five years to 3.33 years, results in an increase in the LCOE by 21%. Similarly, an increase of the battery life-time by 33% (6.66 years), would result in a decrease of the LCOE by almost 8%. 
Figure 7. Results of the sensitivity analysis on the expected LCOE for the various systems: a) impact of number of years of operation; b) impact of LNG price on the 10-year LCOE. The error bars represent the standard deviations computed through the uncertainty analysis.

Figure 8. Local sensitivity analysis: impact of the uncertain parameters on the estimated LCOE.
4. Discussion

The results of the study suggest that it is technically feasible to produce emission-free power during harbor stays with the proposed system. The use of a two-tank system is shown to lead to the highest energy production. However, the need to have two separate storage tanks results in higher demands in terms of space.

Corvus Energy [32] supplies containerized battery systems for vessels, claiming that a standard 40-foot container (roughly 67.6 m$^3$) could be filled either with a battery package of 1,365 kWh or with a battery package of 819 kWh plus the required power electronics. Given that the considered ferry requires a battery system of 1,500 kWh plus the power electronics, it is expected that the battery system would require a space equivalent to almost two 40-foot containers. This means that the space requirement of the battery and ORC systems are similar.

Further investigations need to be conducted in order to demonstrate the practical feasibility of installing the proposed stratified tank on board a vessel. In particular, there is a need to understand whether the ship motion would have a negative impact on the thermal stratification inside the tank. This issue could be partly addressed by including in the tank a physical separation layer between the hot and the cold zone [33]. Moreover, in order to keep the thermal stratification within the tank, a form factor needs to be applied for the tank. In this case, the use of the form factor results in a tank with a diameter of 3.5 m and a height of 7.1 m. On the contrary, the two-tank solution is not bound to any specific form factor, giving the freedom to design the tanks for optimal integration on the ferry.

With respect the impact of the considered sailing profile on the feasibility of the proposed concept, the high energy coverage factors that were attained indicate that the concept could be suitable also for ferries characterized by shorter sailing phases, or by longer harbor stays. In fact, in the considered case, the ORC-TES system was capable of not only of covering the energy demand during the harbor stays, but also to provide a significant share of the electricity required on board during the sailing phases. Longer harbor stays, or shorter sailing phases would reduce the energy production during the
sailing phases, but would not necessarily compromise the capability of fulfilling the energy needs during the harbor stays.

Hybrid solutions featuring both an ORC and a battery system could be investigated; however, such systems would require even more space and result in a higher installation cost.

In addition, it should be pointed out that it would be possible to use shore power to charge the TES by means, for example, of an electrical heater. This would enable further increase in the ORC production and decrease the cruise emissions. This possibility was not taken into consideration in this work, as the aim is to evaluate the feasibility of the concept even in areas/ harbors when shore power connection is not available.

Lastly, more detailed numerical and experimental evaluations should be carried out in order to validate the proposed concept. In particular, the attained results are based on the use of numerical models that do not consider the dynamic behavior of the system (except for the TES). Dynamic effects are expected to have an impact on the overall performance of the system, especially when switching between the various operational modes. However, experimental data that are not available would be needed to develop models to carry out such studies.

5. **Conclusions**

The present paper investigated the implementation of a novel concept to ensure emissions-free power production for cruise ships during harbor stays. The proposed system includes the use of a thermal storage system and an organic Rankine cycle unit. The feasibility of the concept was investigated from both a thermodynamic and an economic perspective, based on a reference route of a cruise ship operating in the Baltic Sea. For the storage tank, two options were considered: a stratified tank and a two-tank system. Thermal oil was considered as the heat storage medium.

The results of the thermodynamic investigations suggest that the use of a stratified storage tank enables the reduction of the volume of the storage unit by 40 % compared with a two-tank system. From the point of view of the attainable energy production, the two considered tank technologies show similar results. The estimated coverage factors are 82.6 % and 82.1 % for the two-tank and the
The attainable daily reductions of the ferry emissions of CO, CO₂, SO₂ and NOₓ are around 15.8 kg, 5.4 ton, 2.9 kg, and 29.1 kg, respectively.

The results of the economic assessment suggest that the proposed system results in a lower levelized cost of electricity than the battery system, when considering an operational life-time of the ferry exceeding 15 years. Moreover, the use of the proposed system results in a reduction of the required fuel for the production of onboard electricity by around 80 %, making its economic feasibility less affected by potential fluctuations in the liquefied natural gas price. The concept is applicable also for other ship types whose sailing profiles are characterized by short harbor stays with a limited onboard energy demand.

For future work it would be relevant to address the following aspects: i) evaluation of the impact of the ship motion on the thermal stratification in the stratified tank; ii) investigation of the feasibility of the proposed concept over a wider range of sailing profiles; and iii) study of possible hybrid solutions featuring both TES and battery systems.

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References


Nomenclature

Acronyms

1D  one dimensional
CEPCI  Chemical Engineering Plant Cost Index
CO  carbon monoxide
CO\textsubscript{2}  carbon dioxide
CSI  Clean Shipping Index
ESI  Environmental Ship Index
GHG  greenhouse gases
LCOE  levelized cost of electricity, $/kWh
LNG  liquefied natural gas
NO\textsubscript{x}  nitrogen oxides
ORC  organic Rankine cycle
O&M  operation and maintenance
SO\textsubscript{2}  sulphur dioxide
SO\textsubscript{x}  sulphur oxides
TES  thermal energy storage
WHR  waste heat recovery
Symbols

\( A \) area, m\(^2\)

\( E \) electricity generation, $

\( F \) fuel expenditures, $

\( I \) investment cost, $

\( L \) length, m

\( \text{Ntp} \) number of tube passes

\( \text{Ntr} \) number of tube rows

\( P \) pressure, bar / pitch, m

\( r \) ratio, discount rate

\( t \) time, s

\( V \) volume, m\(^3\)

\( \dot{W} \) power, kW

\( y \) year

Greek symbols

\( \eta \) efficiency

Subscripts and superscripts

\( \text{exp} \) expander

\( \text{hex} \) heat exchanger

\( l \) longitudinal

\( \text{sw} \) seawater
tube/transversal