Evaluation of the prospects for waste heat recovery on liquefied natural gas-fuelled ships

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Technical report
Evaluation of the prospects for waste heat recovery on liquefied natural gas-fuelled ships

Final project report
Project summary

The project “Evaluation of the prospects for waste heat recovery on liquefied natural gas-fuelled ships” aimed at deriving guidelines with respect to the optimal integration of organic Rankine cycle-based waste heat recovery units on board ships powered by liquefied natural gas. The project included the development of numerical models and methods to evaluate the performance of organic Rankine cycles. The project is part of the larger project, “Waste heat recovery on liquefied natural gas-fuelled ships”, which included also the realization of an experimental setup at DTU Mechanical Engineering.

In the first part of the project the various heat sources available on board were screened in order to identify the most suitable solution to integrate the recovery unit on board. The possibility to recover the low temperature heat released by the liquefied natural gas during its preheating phase was included among the considered options. The evaluations indicated that the highest savings could be attained by harvesting the heat of the exhaust gases and that fuel saving up to 10% could be achieved.

In the second part of the project, guidelines with respect to the optimal integration of the organic Rankine cycle on board were derived. The guidelines were derived based on considerations regarding the energy savings, the economic performance and the space requirement of the unit. With respect to the optimal design of organic Rankine cycle for maritime applications, it emerged that units operating for larger amount of time and of larger nominal size lead to reduced payback times. In particular, it was estimated that payback times in the range from 5 to 10 years can be expected when installing organic Rankine cycle units on board vessels. For retrofit installations the availability of space on board is an essential parameter that needs to be evaluated.
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1 Introduction

This report summarizes the findings of the project entitled “Evaluation of the prospects for waste heat recovery on liquefied natural gas-fuelled ships”. This project was running in the period from 1st of April 2017 to 29th of February 2020 and the partners of the project were DTU Mechanical Engineering, MAN Energy Solutions, Fjord Line, Alfa Laval, and Lloyd’s Register Marine. Orients Fond and the project partners funded the project. This project was part of a bigger project, entitled “Waste heat recovery on liquefied natural gas-fuelled ships”.

1.1 Background

Due to environmental and legislative incentives and low gas prices, gas-fuelled shipping is expected to increase significantly in the coming years. This is also supported by a recent report from DNV GL [1], which states that there are currently 247 liquefied natural gas (LNG)-fuelled ships and 110 LNG-ready ships, excluding LNG carriers, and indicates that these numbers are expected to increase in the near future.

Concurrently with the growing use of LNG as fuel for maritime applications, increasing efforts are devoted to the study and development of waste heat recovery systems, which enable the conversion of the waste heat released by the marine engines into power, and thus to reduce the fuel consumption of ships. Among the various waste heat recovery (WHR) systems, the organic Rankine cycle (ORC) power systems is considered one of the most promising technologies due to its simple layout and high energy conversion efficiency [2]. The ORC operates in principle similarly to the steam Rankine cycle, but uses an organic compound as working fluid, leading to higher conversion efficiencies when utilized to exploit low to medium temperature heat sources.

The installation of ORC-based WHR systems on board LNG-fuelled vessels is expected to lead to higher savings compared to the installation on board heavy fuel oil-powered vessels. This is mostly due to two reasons. First, LNG-fuelled vessels are characterized by a reduced need for fuel preheating and, as a consequence, a higher amount of waste heat can be harvested by the WHR unit. Second, the absence of sulphur in the LNG results in a relaxation of the WHR boiler design constraints, allowing for the attainment of higher power productions. Lastly, because LNG is stored on board in cryogenic conditions, the low temperature heat released during the fuel preheating process can be used to further improve the performance of the WHR units installed on board.

1.2 Objectives and deliverables of the project

The LNG-waste heat recovery project aimed at evaluating the technical and economic feasibilities of installing ORC-based waste heat recovery systems on board vessels powered by LNG. The project included the development of numerical models to evaluate the techno-economic feasibility of installing ORC units on board ships powered by LNG. The main objectives of the project revolved around the definition of the optimal design, control and integration of WHR units on board LNG-fuelled vessels.
The deliverables of the project are the following:

1. Mapping of the heat sources/sinks on-board of LNG-fuelled ships and identification of the most suitable heat source to be utilized by the LNG-driven ORC unit (see section 2);
2. Proposal on design, control and integration of ORC units as retro-fit solutions and in new-buildings of LNG-fuelled ships (see section 3);
3. Estimation of fuel saving potentials for LNG-fuelled ships; estimation of payback time and net present value for the proposed ORC configurations (see section 3).

1.3 Outline of the report

Section 1 includes a brief explanation of the background of the project and its deliverables. The screening of the available heat sources on board a vessel and the description of novel ORC configurations rejecting heat to multiple heat sources is included in the section. Section 3 provides guidelines with respect of the optimal design ORC units for LNG-fuelled vessels and indications regarding their economic feasibility. Lastly, the dissemination activities of the project are listed in section 4, and the main conclusions are summarized in section 5.
2 Waste heat sources and novel organic Rankine cycle layouts

This section describes the mapping of the available heat sources and sinks on board LNG-fuelled vessels (deliverable 1), and introduces novel ORC architectures rejecting heat to multiple heat sinks.

2.1 Mapping of available heat sources and sinks

A vessel is characterized by a complex energy system and therefore waste heat recovery solutions can be implemented on board in different ways. As shown in Figure 1, four heat sources that can be used for waste heat recovery on board a vessel: exhaust gases, jacket water, lubricating oil and scavenge air.

The lubricating oil has commonly low temperature (around 60–75 °C) [3] and thus is not a particularly attractive source to be considered. The exhaust gases are available at high temperature (above 200 °C) and are commonly utilized for the production of service steam, used to fulfill the heat demands on board [4]. In most cases, the heat contained in the exhaust gases largely exceeds the requirements for service heat – especially when the vessels are operated using low sulphur fuels (i.e. liquefied natural gas), because in these cases there is no need to preheat the fuel [5]. The quality of the waste heat contained in the scavenge air varies significantly as a function of the engine load, both in terms of available energy and temperature level, making it a not so attractive heat source. Lastly, the jacket water is available at a temperature of 80–90 °C, independently of the load at which the main engine is operated. This heat source is suitable to be used for the generation of fresh water and offers the potential for additional utilization by means of low temperature organic Rankine cycle power systems [6].

Regarding the available heat sinks, seawater represents the most commonly preferred solution. Seawater is abundantly available and its temperature is generally in the range 5–30 °C, depending on location and time of the year. Another possibility is the use of air as cooling media. Nonetheless, the poorer heat transfer properties of air compared to water, and its higher temperature variability makes it a less interesting solution, except for particular cases – i.e. ships sailing in the arctic region [7]. An additional heat sink can be considered in LNG fuelled ships. LNG is stored on board at atmospheric pressure in a liquefied state at about -160 °C, making it necessary to heat it up to about 30 °C before injection in the engine. The heat that needs to be provided for evaporation and pre-heating of the LNG can be provided by the heat rejected by an ORC unit, leading to the implementation of high efficiency waste heat recovery units.
Figure 1: Simplified layout of a state-of-the-art machinery system aboard large ships [2].

The suitability of the various heat sources and sinks with respect to their potential for waste heat recovery was investigated through a study that considered a vessel powered by a 7G95ME-C9.5 MAN Energy Solutions dual fuel two-stroke marine engine with low pressure selective catalytic reduction tuning [8]. The CEAS engine calculation tool [9] from MAN Energy Solutions was utilized to retrieve the engine data, shown in Table 1.

Table 1: MAN 7G95ME-C9.5, performance and waste heat sources at different loads.

<table>
<thead>
<tr>
<th>Load [%]</th>
<th>Power [kW]</th>
<th>SFC [g/kWh]</th>
<th>$\dot{m}_\text{ex}$ [kg/s]</th>
<th>$T_\text{ex}$ [°C]</th>
<th>JW heat [kW]</th>
<th>$T_\text{jw}$ [°C]</th>
<th>$\dot{m}_\text{jw}$ [kg/s]</th>
<th>$\dot{m}_\text{LNG}$ [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>36,820</td>
<td>135.8</td>
<td>79.1</td>
<td>261</td>
<td>4,380</td>
<td>85</td>
<td>69.47</td>
<td>1.39</td>
</tr>
<tr>
<td>75</td>
<td>27,615</td>
<td>129.7</td>
<td>60.9</td>
<td>253</td>
<td>3,570</td>
<td>85</td>
<td>69.47</td>
<td>0.99</td>
</tr>
<tr>
<td>50</td>
<td>18,410</td>
<td>127.1</td>
<td>42.6</td>
<td>268</td>
<td>2,760</td>
<td>85</td>
<td>69.47</td>
<td>0.65</td>
</tr>
<tr>
<td>25</td>
<td>9,205</td>
<td>129</td>
<td>22.4</td>
<td>285</td>
<td>1,940</td>
<td>85</td>
<td>69.47</td>
<td>0.33</td>
</tr>
</tbody>
</table>

The study assumed that a portion of the JW heat (400 kW) was used by the onboard fresh water generators, at all engine loads. Similarly, the requirements for service steam were neglected, as they are strongly reduced in LNG-fuelled vessels. Four ORC configurations were investigated. The first two configurations (case A) utilized the main engine exhaust gases and the jacket cooling water as heat sources, while the last two configurations (case B) harvested heat only from the engine jacket cooling water. Seawater
and LNG preheating were considered as possible heat sinks. An overview of the considered heat sources and sinks in the various cases is show in Table 2.

Table 2: Selected heat sources and sinks for the considered configurations.

<table>
<thead>
<tr>
<th>Heat source</th>
<th>Exhaust gases + jacket water</th>
<th>Jacket water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat sink</td>
<td>Seawater</td>
<td>A1</td>
</tr>
<tr>
<td></td>
<td>LNG</td>
<td>A2</td>
</tr>
<tr>
<td></td>
<td>LNG</td>
<td>B1</td>
</tr>
<tr>
<td></td>
<td>LNG</td>
<td>B2</td>
</tr>
</tbody>
</table>

Figure 2 shows a sketch of the considered ORC configurations. Simple ORC configurations were investigated for case B, while configurations of case A included also an internal recuperator and a jacket water preheater (see Figure 2). For this study, the boiler feed temperature lower limit was set to 110 °C (case A configurations only) as to avoid issues related to sulphuric acid corrosion (this corresponds to an LNG fuelled ships using a pilot oil containing sulphur). Taking into account the typical annual load profile of a containership, the four proposed ORC configurations were optimized, screening a variety of working fluids. The objective function of the optimization procedure was the ORC net power production when the engine was operated at 75 % load.

![Sketch of the considered ORC configurations: a) cases A; b) cases B.](image)

Two scenarios were investigated regarding the use of the energy produced by the ORC unit. In the first case, the ORC energy production was used for propulsion and the fuel savings were calculated as:

\[
Fuel\; saving\; (\%) = 1 - \frac{Main\; engine\; annual\; consumption\; (with\; ORC)}{Main\; engine\; annual\; consumption\; (without\; ORC)}
\] (1)

In the second scenario it was assumed that the electricity produced by the ORC unit was used to replace the consumption on the on-board electricity generators, whose average fuel consumption was assumed to be 160 g/kWh [10]. Here the equivalent fuel savings were calculated as:
\[ \text{Equivalent fuel saving (\%)} = \frac{\text{Annual saving in auxiliary engines}}{\text{Main engine annual consumption (without ORC)}} \]  \hspace{1cm} (2)

The results of the optimizations are depicted in Table 3 and suggest that the exhaust gases are the most promising heat source available on board, leading to the highest fuel savings. The use of the jacket cooling water results in significantly lower savings – always below 1 %. Lastly, looking at the configurations utilizing the LNG preheating as heat sink, it appears that this option, despite the possibility of designing high efficiency ORC units (the estimated efficiency reached 35 \% when using the exhaust gases as heat source), yields limited fuel savings. This is because of the limited mass flow rate of the LNG fuel that needs to be preheated, which practically sets a limit to the ORC working fluid mass flow rate and thus to the maximum attainable power output.

**Table 3: Results of the annual simulations for the two selected scenarios.**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Use for propulsion</th>
<th>Use for auxiliary generators</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>8,048</td>
<td>1,075</td>
</tr>
<tr>
<td>A2</td>
<td>981</td>
<td>131</td>
</tr>
<tr>
<td>B1</td>
<td>923</td>
<td>124</td>
</tr>
<tr>
<td>B2</td>
<td>511</td>
<td>68</td>
</tr>
</tbody>
</table>

2.2 Novel organic Rankine cycle architectures

As emerged from the results described in the previous section, the exhaust gases represent the most promising heat source to be utilized for waste heat recovery, because it leads to the highest fuel saving potential. The heat contained in the jacket cooling water does not allow to obtain fuel savings above 1 \% the ship annual fuel consumption. The investigations that aimed at assessing the prospects to use the cold energy contained in the LNG fuel as a way to obtain high efficiency ORC units lead to the following conclusions:

i. The use of the low temperature heat available in the LNG enables the design of high efficiency ORC units (cycle efficiencies up to 23 \% and 35 \%, when using jacket water and exhaust gases as heat sources, respectively);

ii. The LNG mass flow rate is limited and therefore poses a constraint on the maximum power output that can be produced by implementing such high efficiency units;

New ORC cycle configurations were therefore proposed as a way to take advantage of the low temperature of LNG mass flow rate, while getting over the limitations on the maximum power production [8]. The proposed ORC configurations are shown in Figure 3. Two configurations were proposed: in the first case (Figure 3a) the ORC unit harvests heat both from the exhaust gases and the jacket cooling water, while in the second case the jacket cooling water is the only considered heat source (Figure 3b).
The novel proposed configurations builds on the concept of a traditional ORC cycle, while including additional components as a way to exploit the low temperature LNG mass flow rate. In practice, a fraction of the working fluid mass flow rate is supplied to a second expander instead of going through the seawater condenser. The second expander ensures the production of higher net power outputs compared to the cases featuring only the seawater condenser and enables the exploitation of the energy released by the LNG during the preheating process. An optimization procedure based on the case presented in section 2.1 was conducted to assess the potential of the newly proposed configurations in comparison with the traditional cycle layouts.

The results of the optimizations are depicted in Table 4, where the novel configurations are named A3 and B3, for the case using the exhaust gases and the jacket cooling water, respectively. The results suggest that the implementation of the novel configurations leads to an increase of the attainable fuel saving potential. This increased fuel saving potential was estimated to be of in the range 42-66 tons/year, when using the ORC energy production to replace the consumption of the onboard auxiliary generators. The increased complexity of the proposed ORC configurations, and the need to include an additional expander unit, makes it however challenging to foresee that the proposed configurations will outperform the traditional layout in terms of economic attractiveness. For further information regarding the novel ORC architectures, see Ref. [8].
Table 4: Results of the annual simulations for novel ORC configurations in comparison with the traditional cycle layouts.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Use for propulsion</th>
<th>Use for auxiliary generators</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ORC production</td>
<td>Fuel saving</td>
</tr>
<tr>
<td></td>
<td>[MWh]</td>
<td>[ton]</td>
</tr>
<tr>
<td>A1</td>
<td>8,048</td>
<td>1,075</td>
</tr>
<tr>
<td>A3</td>
<td>8,497</td>
<td>1,136</td>
</tr>
<tr>
<td>B1</td>
<td>923</td>
<td>124</td>
</tr>
<tr>
<td>B3</td>
<td>1,191</td>
<td>160</td>
</tr>
</tbody>
</table>

2.3 Summary of findings

The exhaust gases and the jacket water are identified to be the most attractive heat sources on board vessels. The use of seawater is recommended as heat sink, while air can be an interesting solution for ships sailing in the arctic region.

The installation of an organic Rankine cycle using the exhaust gases as heat source and seawater as cold sink can lead to equivalent fuel savings up to 10%, when considering the use of the produced electricity to replace the consumption on the onboard auxiliary generators. Savings up to 1% can be attained when using the jacket water as heat source.

The use of the low temperature heat released by the liquefied natural gas during its preheating phase before injection to the engine as a cold sink for an organic Rankine cycle can result in cycles characterized by high thermal efficiencies but low net power outputs. Novel organic Rankine cycle architectures featuring two condenser units were presented and enable the use of both seawater and liquefied natural gas preheating as cooling media for the organic Rankine cycle. The novel layouts result in increased power outputs in comparison with the traditional cycle configurations, but are characterized by a higher degree of complexity and are expected to be more expensive;
3 Optimal design of organic Rankine cycle units

This section provides recommendations regarding the optimal design, integration and control of organic Rankine cycle units on board liquefied natural gas-fuelled ships (deliverable 2). In addition, indications are also provided with respect to the attainable fuel savings and economic attractiveness of the proposed solutions (deliverable 3). Considerations regarding the installation of waste heat recovery units in retrofit applications are also included.

3.1 Case studies and design considerations

In order to assess the prospects for ORC-based waste heat recovery on board liquefied natural gas-fuelled ships, two cases studies were evaluated. The first case study considers a long distance containership of middle size which operates in slow steaming mode in Tier II zones. The second case study revolves around a feeder ship operating in Tier III areas which utilizes exhaust gas recirculation in order to fulfill the requirements of reduced NOx emissions. Table 5 provides an overview of the two considered ships, the installed engines and the annual fuel consumptions. The profiles of the exhaust gases temperatures and mass flow rates are reported in Ref. [11] and Ref. [12] for the feeder and the containership, respectively.

Table 5: Characteristics of the two considered reference vessels

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Feeder</th>
<th>Containership</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>MAN 7S60E-C10.5-GI</td>
<td>MAN 6S80ME-C9.5-GI</td>
</tr>
<tr>
<td>Engine rated power [kW]</td>
<td>10,500</td>
<td>23,000</td>
</tr>
<tr>
<td>NOx emission abatement</td>
<td>Exhaust gas recirculation (Tier III)</td>
<td>Not installed (Tier II)</td>
</tr>
<tr>
<td>Annual operating hours [h]</td>
<td>4,380</td>
<td>6,500</td>
</tr>
<tr>
<td>Annual fuel consumption* [ton]</td>
<td>4,314</td>
<td>9,795</td>
</tr>
<tr>
<td>Engine backpressure [kPa]</td>
<td>3.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

*Propulsion only

The ships not only have engines of different sizes (10.5 MW for the feeder and 23 MW for the containership) but are also operated according to different sailing profiles, as shown in Figure 4. The feeder is mostly operated at high engine loads, while the containership, as previously mentioned, is operated in slow steaming mode. With respect to the optimal design of ORC units suitable to be installed in the considered cases, the following recommendations are provided:

i. Simple non-recuperated ORC cycles are suggested, because of the reduced complexity which leads to reduced investment costs for the units;
ii. Given the negligible content of sulphur in the LNG, there is no need to preheat the working fluid before it enters the waste heat recovery boiler. This is especially true when considering low sulphur pilot fuels;

iii. The use of hydrocarbons as working fluid in the ORC unit is recommended as they are the working fluid candidates leading to the highest energy productions. Hydrocarbons are however flammable fluids, thus special attention should be used when designing and operating the ORC unit (such as using double piping with ventilation and gas leak detection systems);

iv. An off-design control strategy aiming at keeping a constant superheating at the inlet of the turbine is recommended, because it leads to a good off-design performance and it ensures the absence of droplets of fluid at the inlet of the turbine. The presence of fluid droplets would result in severe damage of the turbine.

v. Given that WHR units needs to be economically attractive, it is recommended that the optimization of the design includes economic indicators, ensuring the realization of a unit which is not only recovering high amounts of energy, but is also characterized by short payback times.

![Figure 4: Considered sailing profiles: (a) feeder; (b) containership.](image)

Figure 5 shows a sketch of the considered ORC configurations for the two cases. For the feeder case, the boiler is subdivided into two separate sections, one recovering heat from the portion of the exhaust gases which is recirculated in the EGR unit, and the other one recovering heat from the bulk of the exhaust gases. The validation of the ORC design and off-design models is described in Ref. [13] and Ref. [6], respectively.

The economic attractiveness of the proposed ORC configurations is evaluated by means of two economic indicators, the net present value (NPV) and the simple payback time (PB), calculated as follows:

\[
NPV = -C_{tot} + \sum_{n=1}^{25} \frac{Annual\ savings}{(1 + r)^n} \tag{4}
\]

\[
PB = \frac{C_{tot}}{Annual\ savings} \tag{5}
\]
Where $C_{tot}$ represent the total installation cost for the ORC unit and $r$ is the discount rate, assumed to be 6%. The total installation cost is estimated by using the procedure presented by Turton et al. [14], while the price of the LNG was fixed to 12 $/mmBTU. A 25-years lifetime was assumed when calculating the NPV and cyclopentane was chosen as working fluid for the ORC unit.

![Diagram of ORC configurations](a) (b)

**Figure 5**: ORC configurations: (a) containership; (b) feeder.

### 3.2 Optimized organic Rankine cycle configurations

Table 6 shows the estimated performance of the ORC units optimized for the two considered case studies. As it emerges from the table, the ORC unit are capable of producing a significant amount of energy on an annual basis. If this energy is used to replace the consumption of the auxiliary generator, and assuming a specific fuel consumption of 160 g/kWh for the auxiliary generators, the resulting fuel savings is equal to 6.5% and 8.4% the annual consumption of the main engine, for the containership and the feeder, respectively. In both cases, the PB is estimated to be within 10 years, which should be compared with the 25 year life-time for the vessels.

**Table 6: Results attained for the two considered vessels – ORC designs maximizing the NPV.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Containership</th>
<th>Feeder</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORC design power [kW]</td>
<td>1,204</td>
<td>705</td>
</tr>
<tr>
<td>Volume heat exchangers [m³]</td>
<td>17.00</td>
<td>13.54</td>
</tr>
<tr>
<td>Annual energy production [MWh]</td>
<td>4,014</td>
<td>2,270</td>
</tr>
<tr>
<td>Annual fuel saving [ton]</td>
<td>642.3</td>
<td>363.3</td>
</tr>
<tr>
<td>ORC specific cost [$/kW]</td>
<td>1,784</td>
<td>2,542</td>
</tr>
<tr>
<td>NPV [k$]</td>
<td>2,385</td>
<td>772.7</td>
</tr>
<tr>
<td>PB [years]</td>
<td>6.06</td>
<td>8.93</td>
</tr>
</tbody>
</table>

The higher economic attractiveness of the installation on board the containership is due to a combination of various aspects: i) the containership is operated for a significant higher amount of hours annually; ii) the higher ORC design power outputs results in lower
specific investment costs; and iii) the ORC unit installed on board the feeder features two waste heat recovery boilers, and thus requires higher costs for the components and the installation.

Figure 6 shows the results of the sensitivity analysis on the impact of the variation of the fuel price on the economic attractiveness of the ORC units. As it emerges from the figure, the attainable NPV/PB is highly dependent on the fuel price and the units become more attractive with higher costs of the fuel. In both cases, positive NPVs are expected when the fuel price is at least of 10 $/MMBtu. Simple payback times lower than 5 year are estimated for the containerships when the fuel price is over 15 $/MMBtu. It should also pointed out that the ORC specific cost is a very uncertain parameter which has a significant impact on the estimated economic attractiveness of the units. Large scale implementation of ORC units on board vessels could result in specific ORC prices below 1,000 $/kW and thus to much lower PB times.

![Image of Figure 6](image)

*Figure 6: ORC power production as a function of the WHR minimum pinch point temperature and backpressure supplied to the engine.*

### 3.3 Retro-fit installations

The retrofit installation of ORC units on board vessels represent a challenging engineering task which is characterized by multiple downsides compared to the installation of a WHR on board a new-built vessels. On the other hand, retrofit installations could be considered attractive when considering that novel ships could feature scrubber units, whose operation results in a substantial reduction in the prospects for waste heat recovery.

From a simulation point of view, the installation of an ORC unit in a retrofit case can be investigated by evaluating the impact of having a reduced size of the heat exchangers on the attainable fuel savings/NPV. For the NPV a 25 years scenario is considered, which could lead to optimistic results if the installed ORC is operated for a lower number of years.

Figure 7 shows the impact of imposing a reduced volume of the ORC heat exchangers on the attainable fuel savings/NPV for the case of the containership. As shown in Table 6, the optimal ORC configuration requires a volume of 17 m$^3$ for the heat exchangers.

Reducing space availability to 10 m$^3$, leads to a reduction of the fuel savings by 10 %, and in a reduction of the expected NPV by 8.4 %.
Figure 7: Impact of constraining the volume of the heat exchangers on the attainable fuel savings and NPV. The results are provided for the case considering the containership.

Figure 8 shows the impact of imposing a reduced volume of the ORC heat exchangers on the attainable fuel savings/NPV for the case of the feeder. As shown in Table 6, the optimal ORC configuration requires a volume of 13.5 m$^3$ for the heat exchangers. Reducing space availability to 7 m$^3$, leads to a reduction of the fuel savings by 13 %, and in a reduction of the expected NPV by 19.1 %. More stringent volume constraint are connected to higher reductions in the fuel savings and expected NPVs.

3.4 Summary of findings

This chapters presented guidelines with respect to the optimal design of ORC units to be installed on board ships. The findings indicate that ORC units tailored for marine applications should be designed to maximize their economic effectiveness, which was estimated by means of the NPV of the installation.

The results of the study suggest that the economic attractiveness of installing ORC units increases when with the ship’s sailing time and engine power output (because larger unit have lower specific costs). Moreover, the evaluations carried out for two case studies based on a feeder ship operating in Tier III zone, and a containership operating in Tier II zone indicate that payback times in the range from 5 to 10 years can be expected, depending
on the fuel price. With respect to retrofit installations, the reduced space availability on board the vessel can result in a reduction of the economic attractiveness of waste heat recovery units.
4 Conclusions

The main conclusions of the project are listed in this section, particular focus is posed on the project’s deliverables.

This final report details the main activities carried out throughout the project “Evaluation of the prospects for waste heat recovery on liquefied natural gas-fuelled ships” and summarizes the main results and achievements. The project aimed at providing guidelines for the optimal design and integration of organic Rankine cycle-based waste heat recovery units on board liquefied natural gas-fuelled ships. The project findings are based on the use of validated numerical estimation tools. The following main conclusions can be drawn from the project:

i. Among the different heat sources available on board, the most attractive solutions feature the use of either the main engine exhaust gases or jacket cooling water. With respect to the cooling sink, the use of seawater is recommended, while the use of external air can represent an interesting solution for ships sailing in the arctic regions. The installation of an organic Rankine cycle using the exhaust gases as heat source and seawater as cold sink can lead to equivalent fuel savings up to 10 %, when considering the use of the produced electricity to replace the consumption on the onboard auxiliary generators. The use of the main engine jacket water as an heat source for an organic Rankine cycle can lead to fuel savings up to 1 % of the main engine annual fuel consumption;

ii. It is recommended that organic Rankine cycle to be installed on board vessels are designed to maximize their economic effectiveness. In particular, this increases when with the ship’s sailing time and engine power output (because larger unit have lower specific costs). Two case studies based on a feeder ship operating in Tier III zone, and a containership operating in Tier II zone indicate that payback times in the range from 5 to 10 years can be expected, depending on the fuel price. With respect to retrofit installations, the reduced space availability on board the vessel can result in a reduction of the economic attractiveness of waste heat recovery units;
5 Dissemination

The results of this project were disseminated to both scientific community and industry by means of publications in high impact factor journals, contributions to conferences, and presentations in workshops of relevance in the shipping sector. These contributions are listed in this chapter.

**Scientific journals**


**Conference contributions**


Presentations at workshops


Multimedia

• Project webpage: http://www.whrmaritime.mek.dtu.dk/

Teaching

Results of the project have been disseminated to students at DTU through a course and projects. In the course “41422 Applied Engineering Thermodynamics”, the students were provided with an overview of the project and its main findings during the lecture regarding the utilization of low temperature heat sources for power generations.

In addition, knowledge was transferred to the students during the following projects:

• ‘Performance comparison of Power cycles for low grade heat utilization’, special course.
• ‘Techno-economic evaluation of the implementation of an organic Rankine cycle unit in biomass power plants’, MSc thesis.
• ‘Exploration and investigation of novel solutions to integrate an organic Rankine cycle on board vessels’. BSc thesis.
• ‘Waste heat recovery on passenger vessels for zero-emission power production in harbor’, MSc thesis.
• ‘Optimization of organic Rankine cycle units for waste heat recovery in liquefied natural gas-fuelled tankers equipped with exhaust gas recirculation’, special course.
Bibliography


