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Executive Summary

This deliverable was prepared within WP5. The motivation to implement Waste Heat Recovery (WHR) measures and the working principle of Organic Rankine Cycle (ORC) technology are briefly introduced in Chapter 1. Chapter 2 presents the latest development in implementation of ORC in the maritime sector. In Chapter 3, the vessel's layout and ORCAN's ORC unit are described in depth. The challenges facing the ORC implementation on board as well as the necessary adaptions to overcome them are discussed in Chapter 4. The system's potential and possible savings are evaluated in Chapter 5. Finally, the conclusion and next steps are given in Chapter 6.

Stricter regulations in sectors such as shipping and energy production has been a great weapon to combat global temperature rise and climate change. The International Maritime Organization (IMO) has been rolling out stricter regulations on consecutive stages. WHR methods have been making their way into the maritime sector as a great measure to comply with those new regulations as well as increase the overall efficiency of the vessel. ORC is a great example for WHR technologies. It is a power cycle that captures low grade thermal energy to produce electrical energy. It consists of heat exchangers (evaporator, condenser), expanders, generators and pumps.

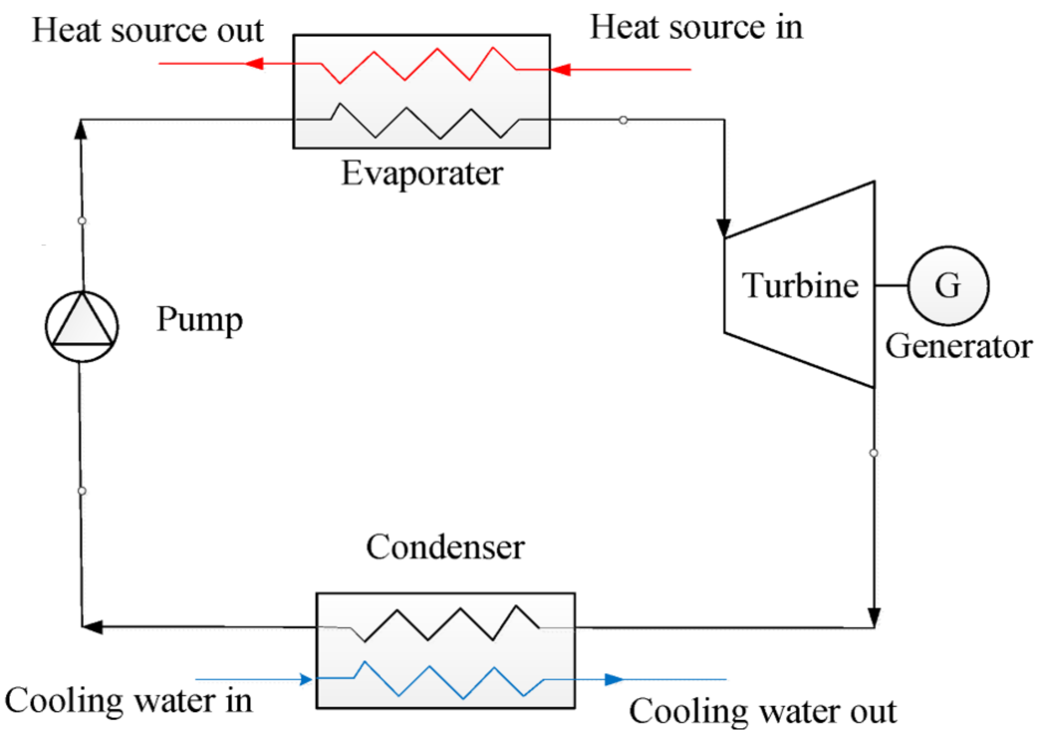

Figure 1: simple ORC layout

ORC utilization in the maritime sector has become an attractive subject for researchers. An ORC can utilize the heat in the exhaust gases of Diesel marine engine, in order to produce electricity and lower the fuel consumption of the vessel. Consequently this will lower the vessel's emissions. Researchers have shown that in order to maximize the benefits of an ORC unit the appropriate working fluid for the available heat source must be selected as well as the most feasible ORC layout. Jacket Cooling Water (JCW) can be used to preheat the working fluid and increase the power output as well as the efficiency of the ORC unit.

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Adopting a compact design could be the best approach to accommodate the space and weight restrictions on-board. On the other hand a robust frame and connection compensators are necessary to protect the ORC unit from any damage or loss of energy production that could be caused by the vibration on-board the vessel.

Retrofitting projects are challenging because the produced steam from the Exhaust Gas Boiler (EGB) is designed for the vessel steam consumers and is not oversized to account for an ORC unit. Installing a heat exchanger directly in the exhaust manifold creates backpressure on the main engine and could cause sulphur condensate if it cools the exhaust gases below their dew point. That is why only the excess steam from the EGB is used.

The main engine is a fluctuating heat source, since it operates in different operational modes. This fluctuation can cause significant drop in the ORC performance and could eventually damage it. That is why it is essential to have a dynamic and responsive control system to keep the ORC operating at its optimum point according to the available heat on the vessel.

The aforementioned adaptions to the ORC make it a very viable option for WHR on-board vessels, as demonstrated by the positive Net Present Value (NPV) obtained in the economical evaluation of the ORC's potential for this project.

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Abbreviations and acronyms

AB	Auxiliary Boilers
AE	Auxiliary Engines
CW	Cold Water
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Index
EGB	Exhaust Gas Boiler/Economizer
EGCS	Exhaust Gas Cleaning System
eP	efficiency Pack
EPL	Engine Power Limitation
FWG	Fresh Water Generator
HW	Hot Water
IMO	International Maritime Organization
JCW	Jacket Cooling Water
NPV	Net Present Value
MCR	Maximum Continuous Rating
ME	Main Engine
ORC	Organic Rankine Cycle
VLCC	Very Large Crude Carrier
WHR	Waste Heat Recovery
WW	Warm Water

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1. Introduction

1.1. Motivation

To address climate change, carbon dioxide (CO_2) emissions must be significantly reduced. For the past two decades, this notion has been the driving force for new and rigorous limitations and regulations in a variety of industries [1]. Consequently, the International Maritime Organization (IMO) has been planning and implementing stricter regulations to reduce vessels' emissions. These regulations are being implemented gradually over multiple stages (tier I, tier II, tier III) [2]. One of the measures to comply with such regulations and reduce emissions is increasing the vessel's overall efficiency by utilizing Waste Heat Recovery (WHR) technologies, such as Organic Rankine Cycle (ORC) [3].

1.2. ORC components and operation principles

ORCs are used to produce electric energy, rather than producing steam from water, the ORC system vaporizes an organic fluid with a larger molecular mass than water. This makes them ideal for harnessing energy from medium-low temperature heat sources or small quantities of thermal energy [4]. For example, the exhaust gases of a marine diesel engine.

Heat exchangers, expanders, pumps and generators are the main components of an ORC. Heat exchangers that capture the available heat and introduces it into the ORC to heat up the working fluid are evaporators. The ones that reject heat from the ORC to the environment in order to cool the working fluid after it expands are called condensers. The type, number and size of used heat exchangers in an ORC varies significantly depending on:

- Working fluid of the ORC (e.g. R245fa, isobutene) the heat-transferring mediums from the heat source (e.g. steam, exhaust gases) and to the heat sink (e.g. air, water).
- Available space since heat exchangers represent the biggest parts of an ORC.
- Budget, heat exchangers are also the most expensive part of an ORC.
- Layout of the ORC, explained in further details below.

Once the working fluid is heated in the evaporator it expands by rotating a turbine and producing mechanical energy, which is then converted into electric energy via an electrical generator.

The working fluid is then cooled in the condenser and finally pumped to a higher pressure. After which it enters the evaporator and the cycle is repeated. The simplest ORC layout can be seen in Figure 2 [5].

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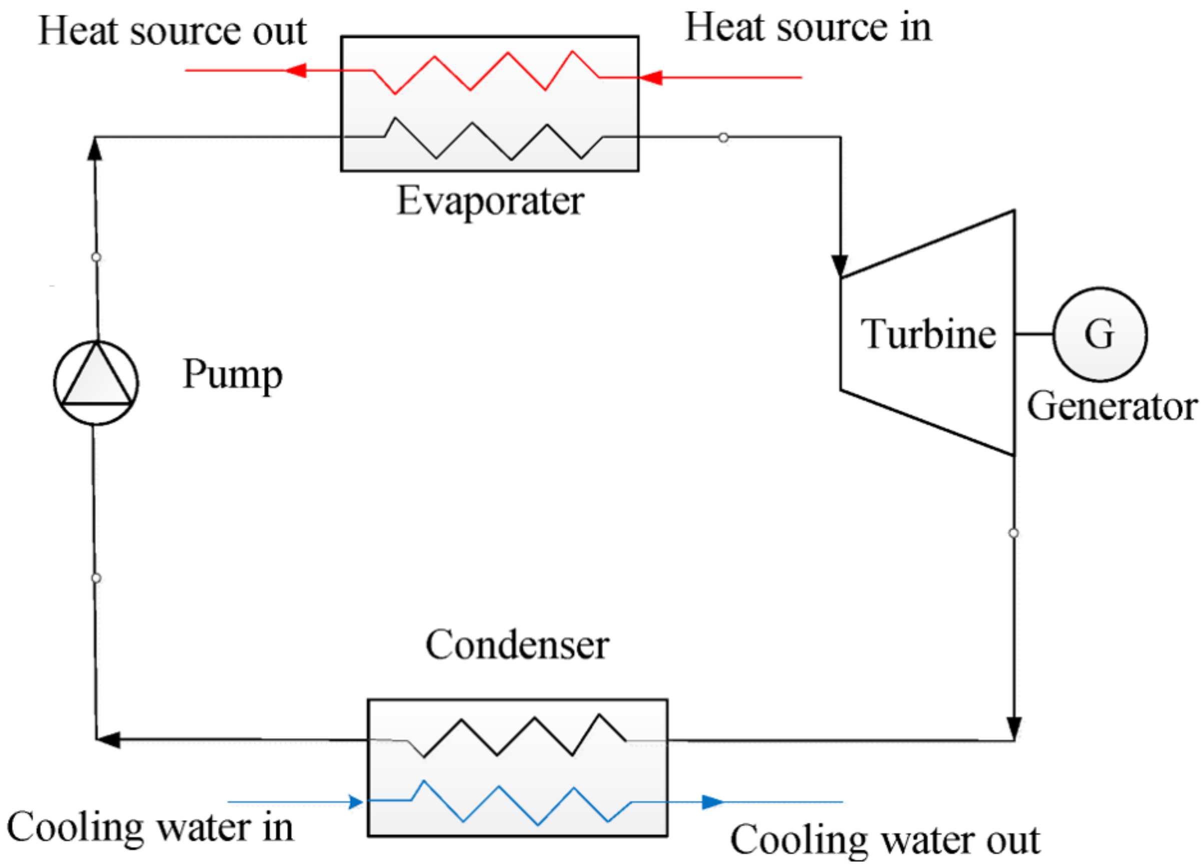

Figure 2: simple ORC layout

A preheater could be added before the evaporator if a secondary heat source is available or a recuperator can be utilized to internally recover some of the remaining heat in the working fluid after it exits the turbine. This can increase the efficiency and lower the area requirements for both the evaporator and the condenser. However, these benefits come with a higher capital investment and a more complex ORC layout that could be unattractive for mobile systems and systems with low operating hours.

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2. State of the Art

One of the highly interesting candidate WHR technologies for the maritime sector is the ORC technology [6]. Researchers have focused their efforts on determining the best ORC configuration, component selection, ORC techno-economic feasibility, and alternative working fluids complying with the most recent developments resulting from regulations for refrigerants.

Other researchers investigated the potential of employing an ORC to recover waste heat from a marine diesel engine. [7, 8] concluded that such a strategy was both environmentally and economically appealing.

Mondejar et al. [9] presented a comprehensive review of the research on the use of organic Rankine cycles for waste heat recovery on board of vessels, as well as an assessment of the possibilities and limitations of using this technology in both, retrofitting of existing vessels and new-built vessels. For three representative operational vessels, the available waste heat and recoverable energies were determined. Guidelines were provided for on-board integration as well as the selection of the best cycle architecture, working fluid, components, and control method. The economic viability was also assessed, as well as the limitations imposed by the integration on board.

According to Baldasso et al. [10], the feasibility of an ORC is strongly dependant on fuel prices as well as heat exchanger restrictions (e.g. space limitations, allowable backpressure on the engine), which varies from one vessel to another. The ORC's economic potential is adversely affected by cheaper fuel and high investment costs associated with large heat exchangers.

The available waste heat on-board of vessels can differ significantly depending on the different operational modes and weather conditions. To that end, Wang et al. [11] evaluated the effects of part load operation on the different components of the ORC rather than its output.

Lebedevas et al. [12] investigated several working fluids and discovered that the choice of the right working fluid is highly influenced by the temperature at which the heat is provided to the ORC. And that the ORC output might vary by 10% for different working fluid choices under the same conditions.

Song et al. [13] demonstrated that the use of the jacket cooling water (JCW) from the main engine for preheating and the exhaust gases from the main engine for the evaporation was economically more attractive than using two separate cycles to exploit the different heat source. Even if the latter configuration produced more energy and showed a higher system efficiency, it still had a significantly higher capital cost.

What sets this research effort apart from other studies is the holistic approach and the actual demonstration of the designed ORC on-board the vessel. This allows the collection of actual data from its operation using the Energy Management System, installed by METIS. This will provide data for validation of simulation models and it will give insight into expected and unexpected challenges when integrating the ORC.

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3. System Layout

In this chapter the demo-vessel and ORCAN's efficiency Pack are described in detail.

3.1. Demo-vessel: Princess Vanya

3.1.1. Vessel specification

The vessel participating in the project is Princess Vanya; a Very Large Crude Carrier (VLCC) tanker built 2012 with cargo carrying capacity of 319,000 tons and max speed of 16 knots. The vessel is engaged in the tramp sector, trading mostly between US, Arabian Gulf and East Asia. Under normal circumstances, the voyages typically range between 10 and 45 days adding up to a total of 180 to 220 sailing days per year[1]. Table 1 to Table 3 below, provide information on vessel's principal dimensions, capacities and the Power-Steam plant.

Table 1: Principal Dimensions

length	(O.A.)	333m
breadth	(MLD)	60m
draft	(scantling)	22.64m
deadweight	(at scantling draft)	319,000t

Table 2 : List of capacities

No	type	capacity (t)	mode
10	cargo tanks	335,806.8	98% full
13	water ballast tanks	99,310.3	100%full
8	heavy fuel tanks	9,173.8	98%full
3	diesel tanks	536	98%full

Table 3: Vessel power-steam plant

No	Unit	Maker/Model	Rated Output
1	Propulsion Diesel Engine	Wartsila 7RT-Flex84T-D	29400KW @ 76rpm
3	Diesel Generator	Yanmar 8N21AL-GW	1360KW @ 900rpm
2	Auxiliary Boiler	Aalborg Mission D Type	45000Kg/h @ 0.7/1.6Mpa
1	Exhaust Gas Boiler	Aalborg Mission XW	3100Kg/h @0.7Mpa

The vessel's energy supply consists of a main propulsion diesel engine and three auxiliary diesel engines coupled to generators for electrical power production. An Exhaust Gas Boiler/Economiser (EGB) uses the exhaust gas of the main propulsion engine. Downstream of the EGB, an Exhaust Gas Cleaning System (EGCS) will be retrofitted that will allow vessel to comply with IMO regulations on the sulphur emissions while consuming high sulphur bunker fuels.

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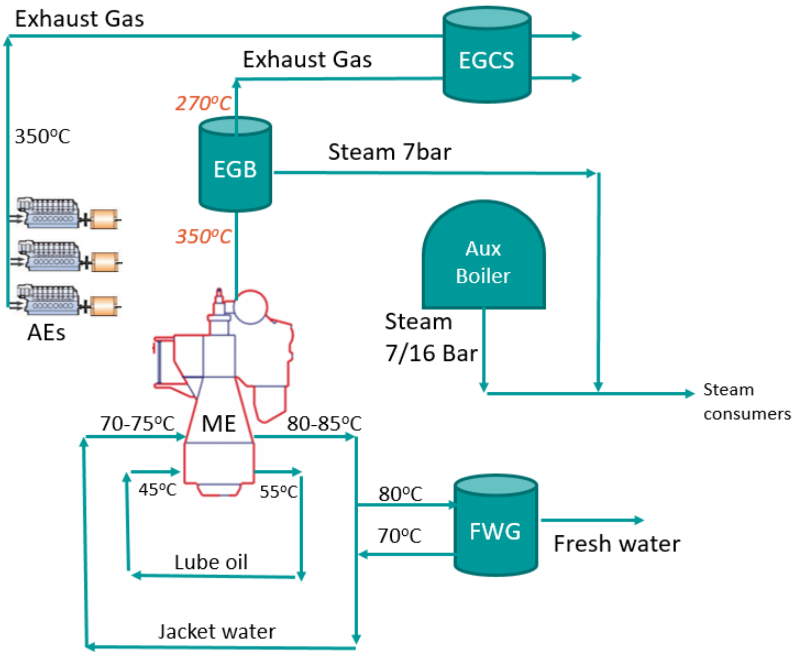

Figure 3: Schematic of Power-Steam Plant design with typical operating temperatures of mediums. (ME)Main propulsion engine, (AEs) Auxiliary Engines, (EGB) Exhaust Gas Boiler, (EGCS) Exhaust Gas Cleaning System - Scrubber, (FWG) Fresh Water Generator.

3.1.2. Available waste heat

Waste heat can be found primarily in exhaust gases from diesel engines, excess steam from the steam plant and excess heat in process streams used to cool the engine (i.e. water/lubricants). Vessels engaged in long distance shipping must be self-sufficient for prolonged periods at sea. For this reason, utilisation of parts of the waste heat is already taking place on-board.

The universally adopted design of these vessels includes the utilisation of waste heat from exhaust gases of the main propulsion engine through the Exhaust Gas Boiler (EGB) to produce steam (Table 3). The downside of these EGBs is that they increase the back pressure to the engines' air-gas path that will adversely affect efficiency and fuel consumption. Increased back pressure along with smaller exhaust flowrate are the main reasons why EGBs are not installed at the exhaust path of the auxiliary diesel engines. Exceptions to this rule are vessels with electrical propulsion but these are often coastal vessels engaged in short voyages.

The EGB is sized so as to meet the demand of the steam consumers in operation while vessel is sailing allowing it to be self-reliant and to minimise the overall fuel consumption. Replacing those steam consumers with electrical ones would increase vessel's overall fuel oil consumption. Additional steam consumers mostly dedicated to the cargo only operate while the Auxiliary Boilers (AB) run. Unlike the EGB the ABs consume additional fuel which reduces overall efficiency and increases the overall emissions of the vessel. Examples of such heavy consumers are the heating coils at the bottom of the cargo tanks, the cargo-tank cleaning machines or the cargo pumps that operate when vessel is discharging cargo to a port/offshore facility. Table 4 shows the list of major steam consumers on-board the vessel including info on steam source.

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Table 4: Steam consumers

No	heat consumer	runs on EGB steam	runs on ABs steam
2	M/E F.O. heater	yes	yes
2	A/E F.O. heater	yes	yes
2	Boiler F.O. heater	yes	yes
2	H.F.O purifier heater	yes	yes
2	L.O. purifier heater	yes	yes
1	Calorifier	yes	yes
1	M/E JCW preheater	yes	yes
6	F.O. tanks heating coils	yes	yes
4	L.O. tanks heating coils	yes	yes
2	Tank cleaning heater	no	yes
17	Cargo tank heating coils	no	yes
3	Cargo pumps	no	yes
1	Ballast pumps	no	yes

The majority of the steam consumers of the vessel are to heat the bunker fuel and lubricants at several stages from storage to purification and final delivery to the engines. As such, these consumers operate both when vessel is sailing and when it is at port. The number of units operating and their respective steam consumption will depend on the ambient conditions (air/sea water) and the quality of the bunker fuel. In cases of low-quality bunker fuel both purification units will be deployed whereas higher viscosity fuel grades will require more heating to reach the viscosity range of 2-12 cSt[1] that is acceptable for the appropriate injection and atomisation of the fuel in the main engine. Any excess steam that is not consumed from the installed equipment will be directed to the condenser units (atmospheric and vacuum condensers) and will be fed back to the EGB or ABs to be heated again for steam generation.

Apart from the steam generated from the waste heat of exhaust gases, waste heat from the jacket cooling water of the main propulsion engine is also utilised for the generation of fresh water on board. The Fresh Water Generator (FWG - Figure 3) simultaneously works as a cooler to reduce the jacket cooling water temperature coming from the engine. When FWG is not running a separate cooler operating with sea water will be deployed which required an electric sea water pump to run.

The theoretical waste heat as discussed above can be estimated from the rated output of consumers installed and steam balance tables of the vessel. The latter are being prepared at the delivery of the vessel by the shipbuilding yard. However, the actual waste heat depends on the working conditions, the seasonality and specific needs of the vessel on each trade route. All theoretical data is acquired basis vessel sailing close to Maximum Continuous Rating (MCR) of the ME. For the past decade global trade requirements (just in time-JIS arrival), increasing

[1] Centistoke is the commonly used unit to describe kinetic viscosity (1 cSt = 1 mm2/s)

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bunker fuel prices and environmental concerns have dictated lower sailing speeds and decreased fuel oil consumptions. In the case of the main engine performing at a load less than 45%MCR, the vessel is considered sailing at slow-steaming conditions. The EGB may underperform under such conditions and the Auxiliary Boilers may also run for the vessel to cover its steam demand. As auxiliary boilers add to the overall fuel oil consumption of the vessel it is common practice to find the optimum operating point for the vessel to minimise consumption and respective emissions while still meet the commercial targets.

The quantification of the actual waste heat available should rely on measurements of the vessel equipment over a prolonged period of time that will include sailing at different navigational speeds and routes under both summer and winter conditions. Main engine parameters as the exhaust and cooling water temperatures, the EGB steam generation and influx of excess steam to the condensers will be required to accurately quantify the waste heat available. Typical design includes sensors only at most critical parts of the vessel which are needed to monitor the relevant parameters for the actual operation. Additional instrumentation is necessary for ORC integration in order to monitor ORC performance and energy efficiency increase.

3.2. ORC Module

The efficiency Pack (eP M 150.200) is a modular system for generating power from waste heat on the basis of ORC technology. Various waste heat flows may be used, such as exhaust gas or cooling water heat from a combustion engine (diesel or gas) or similar sources of heat in marine applications (steam, thermal oil, etc.).

The energy output of the ORC system is converted into electricity to supply the on-board grid. Compared to many other sources of energy on vessels the efficiency Pack generates power without additional CO_2-emissions and is compatible with the waste heat of various fuels and processes.

The operation needs no human intervention except regular visual inspections and is mostly maintenance-free.

Efficiency PACK / E-Power

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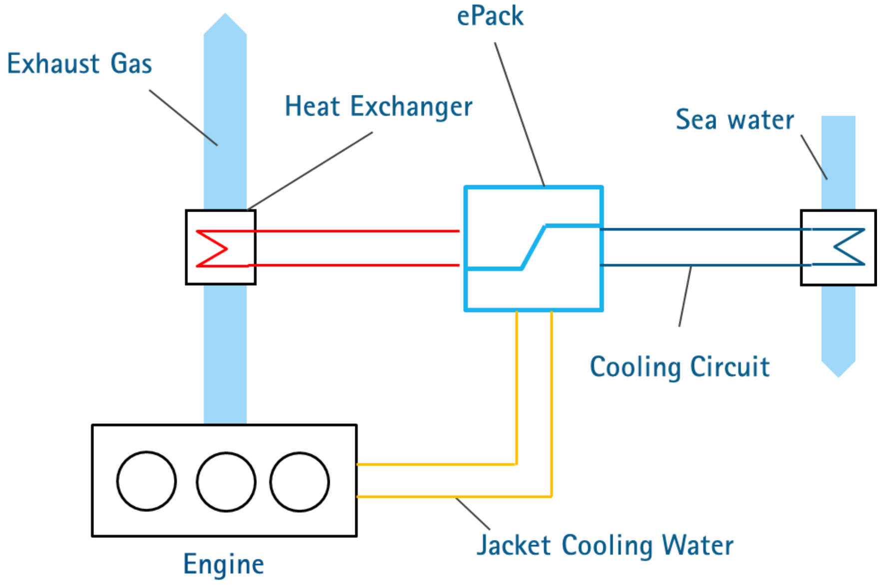
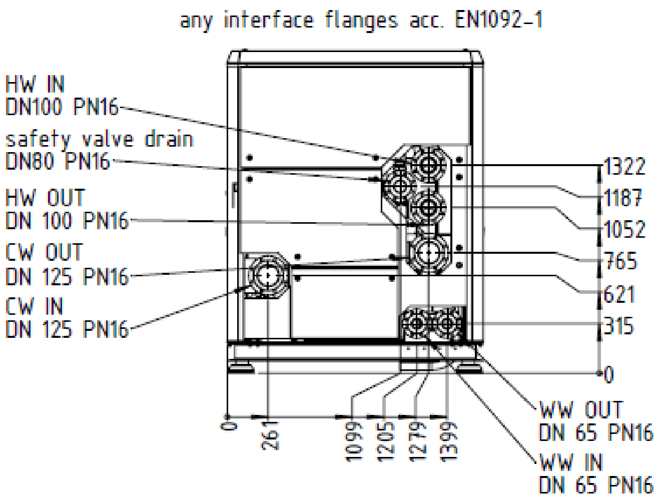


Figure 4: waste heat recovery with ORC technology (efficiency Pack)

3.2.1. Module specifications and integration concept

The efficiency Pack can utilize 1000 - 2100 kW of thermal energy to produce up to 200 kW of electrical power. With its compact design, it only requires 3.9 m^2. On the ORC module, the water loops are connected through standard flange connections on one side of the module, as



shown in Figure 5.

Figure 5: eP M 150.200 connections

The module needs two heat source levels (HW IN from 110 - 145 °C, WW IN from 75 - 109°C) and one cooling water level (CW IN from -5 - 40°C).

The hot water loop will be connected to a steam heat exchanger as the high temperature heat source. The low temperature heat level will be connected to the jacket cooling water system of a combustion engine. The low temperature heat source is used for the preheating inside the ORC process.

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The cooling water loop transfers the heat of the condensation of the ORC to the ambient. In this case the cooling water loop is connected to a sea water heat exchanger transferring the heat to the ambient sea water.

On the electrical side the generator is connected to the main switchboard of the vessel providing power to a connected system.

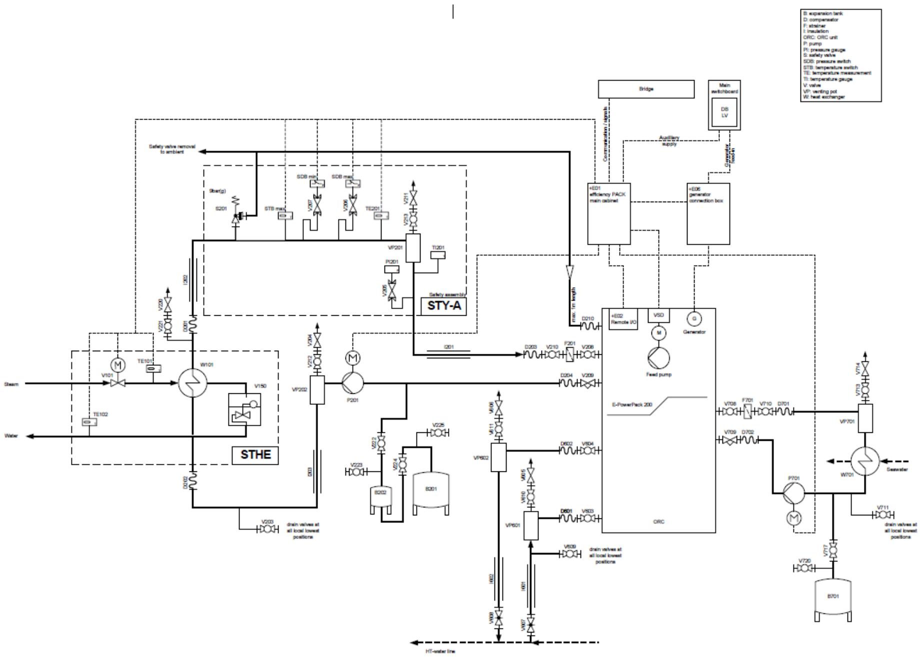

Figure 6: P&ID diagram of the ORC integration

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4. ORC Modules Adaption for Long Distance Vessels

4.1. Challenges for the exploitation of available waste heat on vessels

A general overview of the major obstacles to implementing ORC technology in the maritime sector, followed by a thorough description of how they affect this project specifically.

4.1.1. Volume and weight restrictions

WHR technology in mobile applications competes with potential freight volume and its weight might cause higher fuel consumption. The weight of the ORC could be negligible for bulk carriers and VLCC but might be more significant for smaller vessels and land-based vehicles. The ORC unit is considered economically feasible when the fuel savings are higher than the increase in fuel consumption due to the additional weight and the loss in revenue due to the lost freight [14].

4.1.2. Exhaust gases dew point

Heavy Fuel Oil contains sulphur. Due to that reason the exhaust gases cannot be cooled below the dew point of sulphur in order to avoid sulphur condensation, which causes technical and environmental issues.

4.1.3. Backpressure from additional heat exchangers

As already outlined in section 3.1.2, installing heat exchangers in the exhaust of the main engine will increase the backpressure and consequently increase the fuel consumption. However, an optimal point can be found where the overall efficiency of the system is maximized, i.e. the difference between the fuel savings from the ORC integration and the increase in fuel consumption due to back pressure in the engine is highest

Baldasso et al. [15] investigated the effects of increasing the back pressure on the main engine in order to obtain a higher output from the ORC and found that the fuel savings increased and for the same ORC output the space requirements were reduce significantly when increasing the backpressure. However, this conclusion relies heavily on the main engine’s sensitivity to backpressure as well as the ORC configuration.

4.1.4. Heat source fluctuation

A vessel has different operational modes, in which the available excess heat on-board the vessel can vary greatly depending on the engine power, which impacts the temperature of the exhaust and hence the excess heat. The heat consumption also changes in these different modes which will affect the available heat for the ORC. Finally, the heat consumption as well as the available condensation temperature for the ORC unit will be affected by sailing conditions (e.g. water temperature).

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As demonstrated by Wang et al. [11], if the ORC unit cannot dynamically react to such fluctuations it could cause damage to certain components or even failure. For example, it could cause cavitation in the pump.

4.1.5. Vessel motion and vibration

Vibrations adversely affect the energy generation from the ORC unit, as the turbomachinery cannot operate at their design point. Vibration can also cause early failure of those components and could even cause great damage if they resonate with the harmonic frequency of those components [16].

4.1.6. IMO regulations

The IMO is taking measures to reduce the emissions of greenhouse gases of global shipping. This is an effort to contribute to the collective endeavour of 196 parties that signed the Paris Agreement for climate change to limit global warming to below 2 or preferably below 1.5 degrees Celsius compared to pre-industrial levels.

On 2013 IMO introduced the Energy Efficiency Design Index (EEDI) where all new-build vessels must comply with certain efficiency levels. This Index will be revised to become more stringent in phases so as to incentivise towards technological advancements in the sector. For existing vessels, the Energy Efficiency Existing Ship Index (EEXI) will be introduced as of 1st January of 2023. According to the regulation all existing vessels will have their index calculated based on the formula given below and the result must fall below the threshold in place for the specific type and size of vessel.

$$EEXI = \frac{(MEcons + AEcons) * Emissions\ Factor - (energy\ saving\ from\ Shaft\ Generators\ etc)}{DWT * Vref} \text{ [gCO2/tonmile]}$$

The majority of existing fleet vessels built prior to 2013 fall short to comply with EEXI regulation by margins that range between 10 to 30%. As such, significant measures should take place to ensure compliance. It is evident from the formula that to achieve low numbers of EEXI, the installed power and specific fuel consumption of engines should be small and the carrying capacity and navigational speed should be high. For existing hull forms and current technology on engines, permanent reduction of maximum power (MCR) will yield the higher reduction to the index should there is excess propulsion power. Apart from reduction to the MCR of the main engine, increase of deadweight or the introduction of energy efficiency devices may be used to increase vessel's efficiency and lower EEXI value below the required threshold.

As discussed in paragraph **Error! Reference source not found.** global trade has led to lower s ailing speeds being established on commercial vessels. Main propulsion engines do not currently operate at high loads (>70%). Engine power limitation (EPL) will as a result be the preferred method of compliance without significantly affecting vessels trading capabilities. In cases of hull forms that are not very efficient, significant engine power limitation will adversely affect maximum vessel's reference speed. In these cases, hull efficiency enhancing devices as propeller ducts, redesign of bulbous bow, air lubrication will assist in maintaining or marginally increasing the reference speed.

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Another approach would be to install energy efficiency devices such as heat recovery systems that will decrease the specific fuel oil consumption of the installed auxiliary power. Installing the ORC system on Princess Vanya will allow the vessel to improve its efficiency rating by relying less to the auxiliary engines that consume fuel oil.

The reduction of the MCR of the main engine on Princess Vanya will result on the EGB working at a new maximum point that is lower than what is stated on the original specification of the vessel and the steam balance calculations provided when it was built. Installation of the appropriate sensors and remote monitoring of the vessel parameters while sailing as stated in paragraph **Error! Reference source not found.** will provide the required data to evaluate the p otential of the ORC installation.

4.1.7. Unit certification

The efficiency Pack is a non-essential equipment on-board a vessel. Nevertheless, it needs to meet all class requirements regarding the safety to be allowed on-board. The requirements contain material safety, fire safety, safety of pressure equipment, electrical safety, etc. The compliance with the relevant rules will be approved by the class society through a unit certification.

4.1.8. Installation restrictions

As discussed in paragraph **Error! Reference source not found.**, the integration of the ORC s ystem is materialised on three different levels to collect available heat; steam or exhaust gases side, main engine jacket water side and cooling water side. For each of these levels a new calculation of the closed piping network should take place so that the operation of main propulsion unit is not to be affected. This involves pressure drop calculations to ensure that sufficient pressure is available at inlet of all pumping systems as well as delivered mass-flow rate that satisfies each application requirement.

The integration of the ORC system via new tie-in points requires that certain piping sections are isolated and this cannot be achieved while the vessel is operational. As such it is common for these retrofits to take place during the vessel's dry-docking. Every vessel belonging to long-distance shipping (bulk carriers, tankers, containerships and general cargo vessels) has to undergo a dry-docking once every 5 years until the age of 15years and later on, twice every 5 years. Princess Vanya is due on October 2022 for her 10year dry-dock. Classification societies allow of a window of 3 months prior and after the anniversary date for the vessel to complete its dry-docking.

If the engineering study for the ORC integration has not been delivered by the dry-docking date, then alternatively the consortium can identify the specific tie-in points for the system so that the integration of these can take place in dry-dock. It is then possible for part of the retrofit to take place while vessel is in operation. Nevertheless, for the connection of remaining parts vessel has to request immobilisation by Port Authorities. Welding also requires permission (hot work) which is considered dangerous on tanker vessels as they carry flammable cargo and it will be prohibited when vessel is in the vicinity of Loading/Discharging Facilities. Finally, the routing of all new piping and integration of the generator of the ORC unit to vessel's power grid has to be approved by the classification society of the vessel.

4.1.9. Retrofitting difficulties

In new-build vessels, the ORC's steam demands are included when sizing the EGE. However, when retrofitting it is difficult to acquire the required amount of steam. It is not feasible to install a new heat exchanger to extract the waste directly from exhaust gases. This is mainly due to the corresponding high costs and the additional backpressure on the engine as well as space limitations in exhaust manifold.

4.2. Design adaptions of the ORC modules

To be used on-board, the ORC system has to fulfil the requirements of maritime class societies that deviate from the requirements of land-based products. Those deviations result in changes from a design for land-based systems (e.g. pressure vessel design).

4.2.1. Compact design

In order to facilitate an installation on-board of a large number of vessels a low specific footprint of the system is required. Space in an engine room is limited, so a compact system is key to enable the integration on vessels of different sizes and applications.

4.2.2. Intermediate heat transfer loop

A hot water loop transfers the waste heat of various heat sources to the ORC system. That way the ORC itself is a standardized product with only the integration of heat to the hot water loop being specific to the application.

This approach allows for a solution with the lowest overall cost. Furthermore this solution avoids the overheating and potential thermal damage of the working fluid, especially when using heat sources with very high temperatures like thermal oil or exhaust gas.

4.2.3. Dynamic response to heat source fluctuations

The efficiency Pack is a completely automated system that operates depending on the available heat. It can operate on a wide range from low part load to full load depending on the available heat from the heat source.

It can follow and cope with all gradients of available heat. If the amount of heat is sufficient to reach the starting temperature, the efficiency PACK starts automatically and consumes then a basic heat flow. It the thermal load increases, the efficiency PACK automatically adjusts its load point in order to consume the available heat and transform it into electricity. If the heat load decreases and falls below the switch-off threshold the efficiency PACK shuts down and brings itself into the position of an immediate automatic restart.

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4.3. On-board integration adaptions

At this point the most promising integration on-board a demo-vessel appears to be to use the excess steam of the existing steam system that is not used for other steam consumers.

4.3.1. Utilization of available steam

Since a dedicated heat exchanger for the ORC is not feasible, the waste heat is extracted from the available excess steam generated by the EGE. The excess steam is used in the ORC by transferring the steam to the hot water loop. Therefore, a heat exchanger including steam control valve and a hot water loop will be installed on-board. The size and output will be defined depending on the available steam.

4.3.2. Seawater utilization for cooling

A sea water heat exchanger will be used as a heat sink in order to cool the condensation heat of the ORC process. This sea water heat exchanger is connected to the cooling water loop of the ORC. In this way the ORC can use the lowest available temperature level for its condensation pressure level and thus generate power with the highest possible efficiency.

Higher temperature level such as in central cooling systems would reduce the efficiency and therefore the output of the ORC significantly.

4.3.3. Adapted assembly

The ORC is integrated in a welded steel frame and connected to the water loop by steel piping. It is recommended to use compensators in the pipe connection to the ORC in order to decouple the ORC from the vibration of the vessel as well as to allow for thermal expansion of the pipes connected.

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5. System Potential

A breakdown of the theoretical potential on the demo-vessel and the corresponding economical potential.

5.1. Theoretical potential

The amount of usable heat and rejected heat are needed to estimate the ORC's potential of power production on-board the demo-vessel. However, it was not possible to determine the exact amount of available excess heat due to lack of actual steam data production in the EGB and steam consumption. So the initial step was to estimate the output of the efficiency Pack as a function of the available steam. As shown in Figure 7.

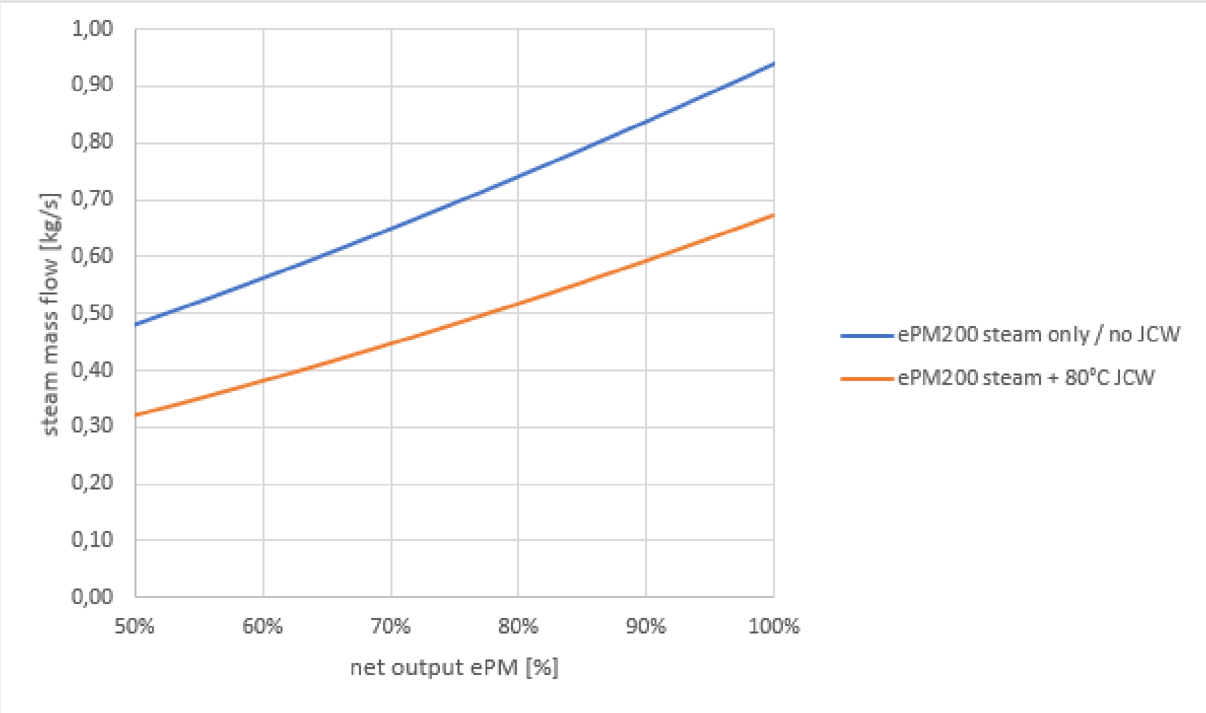

Figure 7: Steam requirements of the efficiency Pack

The blue curve represents the output of the ORC unit without any available JCW for preheating. On the other hand, the orange curve represents the output in the case of sufficient JCW for preheating. Consequently, the unit will produce more power with preheating for the same amount of available steam.

The following assumptions were made to produce those performance curves:

- The available steam is saturated at 6 bar.
- The JCW is available at 80 °C and 20 m^3/h
- Cooling source is sea water at tropical conditions (32°C)

The output of the ORC unit is not critically affected by small changes in the pressure of the steam or in the cold source temperature.

In order to have an initial estimate of the actual available steam on-board the demo-vessel, the crew was asked to manually monitor and record readings from the available measurements in the vessel's steam system. After performing a survey that lasted approximately a month, it was

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shown that during that period excess steam was available for approximately 70% of the operational time. However the exact amount of was still unknown.

The development of an estimated steam profile is the next step in the potential analysis. It will be possible to obtain a more accurate estimate of steam consumption and production, as well as the amount of excess steam available for the ORC, by constructing an operational profile of the demo-vessel from the aforementioned survey and combining it with the theoretical steam balance of the demo-vessel.

At a later stage of the project, the necessary instrumentation to measure and quantify the exact amount of excess steam will be installed to allow for a more precise analysis.

5.2. Economic potential

In order to estimate the feasibility of the efficiency Pack, it is necessary to calculate both its cost and the savings it will produce. The capital costs of the ORC are independent of its utilization and thus independent of the steam profile and were calculated according to the Atolfi method [17].

The resulting costs from that method are:

- Investment costs: 678,000 Euros
- Operational costs: 13,500 Euros

Even though this approach is used frequently in research to estimate ORC costs, it must be noted that this method is on the conservative side. The actual cost of an ORC system with its auxiliaries is expected to be lower than the above calculated values. This can be due to technology development or the modular approach of the systems becoming more popular in the ORC industry.

In order to calculate the savings, the following assumptions were made:

- Vessel operating time: 220 days
- Constant amount of excess steam is available on the vessel: 0.6 kg/s
- Avg. diesel price: 1.5 Euros
- Diesel generators efficiency: 30%
- Interest rate: 4%

Since the electricity consumption on-board is high enough, all the produced electricity from the ORC can be utilized. The annual savings were calculated by estimating the savings from lower diesel consumption by the diesel generators and then subtracting the operational costs of the ORC unit from them.

Table 5 presents two scenarios: the first one is with excess steam being available for the entire operation time of the vessel. The second scenario is with excess steam being available only 70% of operating time as the survey, mentioned in the previous section, concluded.

The results of Net Present Value (NPV) indicate that even if the steam is only available for 70% of the time, the ORC unit is an attractive investment if it will be operated more than 10 years.

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Table 5: Savings and NPV estimations of the ORC unit

Excess steam availability	100%	70%
ORC operating hours	5280	3696
Annual savings [€]	158,000	111,000
NPV after 5 years [€]	-186,000	-207,000
NPV after 10 years [€]	237,000	135,000

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6. Conclusion and Future Plans

The increasing interest in researching ORC utilization in the maritime sector reflects the great potential of employing this technology to lower the fuel consumption of vessels and thus lower the emissions resulting from long-distance shipping. However, installing an ORC on-board a vessel entails many challenges and requires innovative solutions and adaptions to make the technology suitable for the maritime sector.

The compact design of the ORC unit is crucial, since there is limited space on-board to integrate it and due to the fact that it competes with possible cargo (i.e. potential earnings). A combination of a robust frame and connection compensators protects the ORC unit from any damage or loss of energy production that could be caused by the vibration on-board the vessel.

For retrofitting projects, such as this one, the produced steam from the EGB is used instead of tapping into the exhaust gases directly. This is to avoid increasing the backpressure on the engine by introducing a new heat exchanger in its exhaust manifold. Another reason is the risk of cooling down the exhaust gases to their dew point, which can result in sulphur condensation.

A standardized ORC unit lowers the overall cost of the technology integration. This standardization is possible due to the use of an intermediate loop, which can be adapted to each application to recover the needed heat and transfer it to the ORC unit. This also protects the working fluid from degradation.

Lastly, the ORC unit has dynamic control system that allows it to cope with the fluctuations in the available excess heat aboard a vessel due to the different operational modes of vessels or the changing heat demand on-board.

The exact amount of available steam on board the demo-vessel is still unknown. Further measurements and monitoring is needed to accurately estimate it. Once the efficiency Pack is tested, pre-commissioned and approved by the class society, it will be installed on-board the demo-vessel “Princess Vanya”.

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7. References

References

[1] A. Sadatshojaie and M. R. Rahimpour, “CO2 emission and air pollution (volatile organic compounds, etc.)–related problems causing climate change,” in *Current Trends and Future Developments on (Bio-) Membranes*, A. Figoli, A. Basile, and Y. Li, Eds.: Elsevier, 2020, pp. 1–30.

[2] T. W. P. Smith *et al.*, *Third IMO Greenhouse Gas Study 2014*: International Maritime Organization, 2015. [Online]. Available: https://www.research.manchester.ac.uk/portal/en/publications/third-imo-greenhouse-gas-study-2014(e43828fb-354c-4459-bfc5-77ac7fa4a181).html

[3] C. Ng, I. C. K. Tam, and D. Wu, “Thermo-Economic Performance of an Organic Rankine Cycle System Recovering Waste Heat Onboard an Offshore Service Vessel,” *Journal of Marine Science and Engineering*, vol. 8, no. 5, p. 351, 2020, doi: 10.3390/jmse8050351.

[4] E. Macchi and M. Astolfi, Eds., *Organic rankine cycle (ORC) power systems: Technologies and applications*. Duxford, UK, Amsterdam, Boston, Heidelberg, London, New York, Oxford, Paris, San Diego, San Francisco, Singapore, Sydney, Tokyo: Woodhead Publishing is an imprint of Elsevier; Elsevier, 2017. [Online]. Available: http://www.sciencedirect.com/science/book/9780081005101

[5] L. Li, Y. T. Ge, and S. A. Tassou, “Experimental Study on a Small-scale R245fa Organic Rankine Cycle System for Low-grade Thermal Energy Recovery,” *Energy Procedia*, vol. 105, pp. 1827–1832, 2017, doi: 10.1016/j.egypro.2017.03.531.

[6] U. Larsen, L. Pierobon, F. Haglind, and C. Gabrielii, “Design and optimisation of organic Rankine cycles for waste heat recovery in marine applications using the principles of natural selection,” *Energy*, vol. 55, pp. 803–812, 2013, doi: 10.1016/j.energy.2013.03.021.

[7] S. Lion, R. Taccani, I. Vlaskos, P. Scrocco, X. Vouvakos, and L. Kaiktsis, “Thermodynamic analysis of waste heat recovery using Organic Rankine Cycle (ORC) for a two-stroke low speed marine Diesel engine in IMO Tier II and Tier III operation,” *Energy*, vol. 183, pp. 48–60, 2019, doi: 10.1016/j.energy.2019.06.123.

[8] George G Dimopoulos, Chariklia A Georgopoulou, and Nikolaos M P Kakalis, *The introduction of exergy analysis to the thermo-economic modelling and optimisation of a marine combined cycle system*, 2012. [Online]. Available: https://www.researchgate.net/publication/267262945_The_introduction_of_exergy_analysis_to_the_thermo-economic_modelling_and_optimisation_of_a_marine_combined_cycle_system

[9] M. E. Mondejar, J. G. Andreasen, L. Pierobon, U. Larsen, M. Thern, and F. Haglind, “A review of the use of organic Rankine cycle power systems for maritime applications,” *Renewable and Sustainable Energy Reviews*, vol. 91, pp. 126–151, 2018, doi: 10.1016/j.rser.2018.03.074.

[10] E. Baldasso, J. G. Andreasen, M. E. Mondejar, U. Larsen, and F. Haglind, “Technical and economic feasibility of organic Rankine cycle-based waste heat recovery systems on feeder ships: Impact of nitrogen oxides emission abatement technologies,” *Energy Conversion and Management*, vol. 183, pp. 577–589, 2019, doi: 10.1016/j.enconman.2018.12.114.

[11] X. Wang, G. Shu, H. Tian, W. Feng, P. Liu, and X. Li, “Effect factors of part-load performance for various Organic Rankine cycles using in engine waste heat recovery,”

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 955413

Energy Conversion and Management, vol. 174, pp. 504–515, 2018, doi: 10.1016/j.enconman.2018.08.024.
[12] S. Lebedevas and T. Čepaitis, "Research of Organic Rankine Cycle Energy Characteristics at Operating Modes of Marine Diesel Engine," *JMSE*, vol. 9, no. 10, p. 1049, 2021, doi: 10.3390/jmse9101049.
[13] J. Song, Y. Song, and C. Gu, "Thermodynamic analysis and performance optimization of an Organic Rankine Cycle (ORC) waste heat recovery system for marine diesel engines," *Energy*, vol. 82, pp. 976–985, 2015, doi: 10.1016/j.energy.2015.01.108.
[14] R. Pili, A. Romagnoli, K. Kamossa, A. Schuster, H. Spliethoff, and C. Wieland, "Organic Rankine Cycles (ORC) for mobile applications – Economic feasibility in different transportation sectors," *Applied Energy*, vol. 204, pp. 1188–1197, 2017, doi: 10.1016/j.apenergy.2017.04.056.
[15] E. Baldasso, M. E. Mondejar, J. G. Andreasen, K. A. T. Rønnenfelt, B. Ø. Nielsen, and F. Haglind, "Design of organic Rankine cycle power systems for maritime applications accounting for engine backpressure effects," *Applied Thermal Engineering*, vol. 178, p. 115527, 2020, doi: 10.1016/j.applthermaleng.2020.115527.
[16] A. Andrearczyk, G. Żywica, Ł. Breńkacz, and P. Bagiński, "Vibration based diagnostics of the multi-stage microturbine operating in the medium-temperature ORC system," *Vibroengineering PROCEDIA*, vol. 13, pp. 56–61, 2017, doi: 10.21595/vp.2017.19024.
[17] M. Astolfi, M. C. Romano, P. Bombarda, and E. Macchi, "Binary ORC (Organic Rankine Cycles) power plants for the exploitation of medium–low temperature geothermal sources – Part B: Techno-economic optimization," *Energy*, vol. 66, pp. 435–446, 2014, doi: 10.1016/j.energy.2013.11.057.

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A. Annexes

I. eP M 150.200 specifications

Thermal Input Power		1000 - 2100 kW
Max. Rated Output (active electrical power)		200 kW electric net 240 kW electric gross
Working Fluid		Standard refrigerant (non-toxic, non-flammable) with POE oil
Design Guidelines		Designed and manufactured according to norms and standards: ■ Pressure Equipment Directive 2014/68/EU ■ Machinery Directive 2006/42/EC ■ EMC Directive 2014/30/EU ■ DNV RU-Ship
Product Components	Hot-water circuit	Safety devices for hot water circuit: safety relieve valve, pressure and temperature limit switches
	ORC system	Compact module containing: evaporator, expansion machine with integrated asynchronous generator, feed pump, bypass valves, plate condenser (water-cooled)
	Electric cabinet	ORC Control system, suitable for remote monitoring, IP54 Main circuit breaker, individual breakers for main consumers Power measurement (for controls, not calibrated for billing) Data interface
	Frequency converter	Variable speed drive for feed pump

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Hydraulic Interface			High temperature water circuit *(heat input)*	Cooling circuit *(condenser loop)*	Low temperature water/ jack-et cooling *(heat input, optional)*
	Permissible operating temperature	°C	+110 .. +145	-5 .. +40	+75 .. +109
	Permissible temperature (TS)	°C	+165		+120
	Volume flow	m^3/h	≥ 60	≥ 80	≥ 20
	Connection	*EN1092-1*	2 x DN100 / PN16	2 x DN125 / PN16	2 x DN65 / PN16
	Pressure	bar_g	5,0 .. 7,5		1 .. 7
	Permissible pressure (PS)	bar_g	10		10
	Composition	-	Demineralized-water with 40 % propylene glycol		Demineralized-water with max. 50 % glycol
Data and Signal Interface			▪ Data exchange to external (e.g. customer energy management system) via OPC UA or Modbus TCP ▪ External enabling signal (ext. floating NOC) ▪ External emergency stop signal (ext. floating NCC) ▪ ORC-OK signal (int. floating NOC) ▪ ORC in operation signal (int. floating NOC) ▪ Internet connection for remote maintenance must be supplied by site operator (ethernet, wireless or cellular)		
Maximum Sound Emission (full load)			Sound pressure level in 10 m distance $L_{pA,10m}$: < 78 dB(A)		
Ambient Conditions			DIN EN 60721-3-6 (applied classes: 6K3, 6B1, 6C2, 6S2, and 6M2) max. +50 °C for electrical cabinet		
Dimensions			Approx. 2200 x 1650 x 2060 mm		
Weight (filled with refrigerant)			Approx. 4.600 kg plus electrical cabinet (approx. 300 kg)		
Storage			< 1 year, DIN EN 60721-3-1 (IE14), rel. humidity < 95 %		
Transport			DIN EN 60721-3-2 (IE 23)		
Operation	Operating time		IEC S1 (continuous operation)		
	Time between overhaul (TBO)		15 years or 120.000 hours		

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Electrical Data

Auxiliaries Supply			
V_{nom}	-	380-415 V (3~+PE), 50 Hz	440-480 V (3~+PE), 60 Hz
$P_{maxSupply}$	*kW*	45	45
$S_{maxSupply}$	*kVA*	57	57
$I_{maxSupply@0,9*VNom}$	A_{eff}	92	76
cos phi	-	0,8	0,8
Integrated main fuse I_{CW} (max. 1 s)	-	none	
Short circuit current capability I_{CW} (max. 1 s)	*kA*	2	
Direct grid connection via generator connection box			
V_{nom}[1]	-	380-415 V (3~ +PE), 50 Hz	440-480 V (3~ +PE), 60 Hz
$P_{nom/max}$	*kW*	240	240
S_{nom}	*kVA*	255	255
$I_{max@0,9*Vnom}$	A_{eff}	390	340
cos phi	-	0.95	0.95
Max. short circuit contribution acc. IEC 61363-1	A_{peak}	2028	2052
Short circuit current capability I_{CW} (max. 1 s)	*kA*	6.0	
Max. short-circuit current breaking capacity I_{CU}	*kA*	55	
Integrated MCCB type and mains connection point	-	3VA2450-5JP32-0AA0	
Generator type	-	asynchronous	
Cooling	-	through refrigerant	
Synchronization	-	automatic	
Crank	-	through ORC	
Start-up current (3 cycle RMS)	kA_{eff}	< 0.5	
Peak inrush current	kA_{peak}	< 1.5	
Integrated compensation	-	yes	

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