Zero waste Heat vessel towards relevant Energy savings also thanks to IT technologies

D1.3 | Market scenarios and on-board boundary conditions for ZHENIT solutions

WP1 – Vessel Audit and Requirement Definition towards Zero Waste Heat

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Clean and competitive solutions for all transport modes - Innovative on-board energy saving solutions

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Abbreviation and Acronyms

Acronym	Description
AHT	Adsorption Heat Transformer
AS	Annual savings
CAPEX	Capital expenses
CHP	Combined Heat and Power
COP	Coefficient of Performance
DPS	Dynamic positioning system
EGB	Exhaust gas bypass
ETS	Emission trading system
HRE	Heat recovery evaporators
ICE	Internal Combustion Engine
IEE	Isobaric Expansion Engine
IMO	International Maritime Organisation
KC	Kalina Cycle
LTES	Latent Thermal Energy Storage
MD	Membrane distillati
MED	Multi-effect desalination
MSF	Multi-stage flashing
NPV	Net Present Value
OFC	Organic Flash Cycle
ORC	Organic Rankine Cycle
OPEX	Operational expenses
PCM	Phase-change material
PTG	Power Turbine and Generator
PTI	Power take-in
PTO	Power take-off
R&D	Research and Development

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SFC	Specific Fuel Consumption
SMCR	Specified Maximum Continuous Rating
SRC	Steam Rankine Cycle
STES	Sensible Thermal Energy Storage
STG	Steam Turbine and Generator
ST-PT	Steam Turbine – Power Turbine (combined system)
TCS	Thermochemical Energy Storage
TEG	Thermoelectric Generation
TES	Thermal Energy Storage
TRL	Technology Readiness Level
WH	Waste heat
WHR	Waste Heat Recovery

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Executive Summary

The ZHENIT Project aims to promote Waste Heat Recovery (WHR) as key and solutions to achieve 2030 International Maritime Organisation and European Union targets for shipping sector decarbonization. The targets of the project are new technologies development, on-board validation, a regulatory framework analysis and a replication roadmap at regulatory and economic level. There are several solutions for recovery of waste heat with different temperatures ranges of application, technology stages, saving potential and efficiencies. The main technologies investigated in the context of the ZHENIT project are: organic Rankine cycles, thermal energy storage, sorption desalination and refrigerationisobaric expansion engines and wind propulsion. There are other technologies either already implemented or with clear potential for marine engine waste heat recovery such as turbocompounding, steam Rankine cycles, thermoelectric generation, absorption refrigeration, organic flash cycles and Kalina cycles.

The present document constitutes the Deliverable D1.3 focused on “market scenarios and on-board boundary conditions for ZHENIT solutions” and is produced within Task 1.4, “market scenarios and boundary conditions for vessels”. This document aims at describing the application context and the requirements for the ZHENIT solution, taking into account real-life needs and constraints that on-board solutions should fulfil, market constraints and the future trends. This report defines the different scenarios for energy- and cost-efficient zero WH on-board such as WH-to-power, WH-to-storage, WH-to-upgrade, WH-to-direct end-use, WH-to-cooling, and WH-to-fresh water, taking into account the end-users needs, the particular technical characteristics of the ship types. Furthermore, this report aims at presenting the market and boundary conditions evaluated as relevant for the implementation of the technical solutions described in different scenarios onboard different categories of vessels. The ZHENIT solutions will be assessed based on the discussed market and boundary conditions regarding the following key criteria: saving potential, technology maturity, and compatibility.

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1 Introduction

This document constitutes the Deliverable D1.3 of the ZHENIT project, focused on "market scenarios and on-board boundary conditions for ZHENIT solutions" and is produced within Task 1.4, "market scenarios and boundary conditions for vessels".

1.1 Context

Prodromal to WP5 activities and capitalizing T1.1 outcomes, this task aims at describing the application context and the requirements for the ZHENIT solution, taking into account real-life needs and constraints that on-board solutions should fulfill, market constraints and future trends.

Based on the initial characterization of the technologies (Task 1.2), this report defines different scenarios for energy- and cost-efficient zero WH on-board, aiming to focus the scope of the ZHENIT integrated solution toward zero-emission waterborne transport.

The formulated scenarios will define integrated interventions for different routes of on-board WH valorization (e.g. WH-to-power, WH-to-storage, WH-to-upgrade, WH-to-direct end-use, WH-to-cooling, WH-to-fresh water), taking into account the end-users' needs, the particular technical characteristics of the ship types and the interactions between WH sources/sinks identified in Task 1.1.

Examples for the combination of the on-board WH valorization integrated interventions will be defined according to energy- and cost-efficient targets, technical boundaries and barriers. This report aims at presenting the market and boundary conditions evaluated as relevant for the implementation of the technical solutions described in different scenarios onboard different categories of vessels. Finally, the ZHENIT solutions will be assessed based on the discussed market and boundary conditions regarding the following key criteria: saving potential, technology maturity, and compatibility.

1.2 Structure of the document

The following sections are included in this document:

- Section 1 (present section): Introduction about D1.3 of the ZHENIT project and its main objectives and the overall structure of the document.
- Section 2: Scenarios for Energy- and cost-efficient Zero WH onboard

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- Section 3: Market and boundary conditions
- Section 4: Applicability of boundary conditions to ZHENIT technology scenarios.
- Section 5: Conclusions

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2 Scenarios for energy- and cost-efficient zero WH on-board

This section aims at presenting the technology scenarios for energy- and cost-efficient zero WH on-board taking into account the end-users' needs, the particular technical characteristics of the ship types. This section defines some examples for the combination of the on-board WH valorization integrated interventions according to energy- and cost-efficient targets.

2.1 Technology scenarios

This sub-section presented six technology scenarios for energy and cost efficient Zero WH onboard ships based on the technologies investigated in the context of the ZHENIT project. These technology scenarios are WH-to-power, WH-to-storage, WH-to-upgrade, WH- to direct end-use, WH-to-cooling, and WH-to-fresh water.

2.1.1 WH-to-Power

Waste heat to power is the heat-capturing process that excess from the combustion process of marine engines to generate power. Generating power from waste heat includes the direct and indirect conversion to electricity. The indirect conversion can be noticed in the power and steam turbines that create mechanical power from the waste heat then it produces electricity by using a generator. However, there are newly developed technologies that can produce electricity directly such as thermoelectric generation.

The power generation from waste heat available onboard ships is dependent on the waste heat source temperatures, therefore, it is considered one of the thermodynamic limitations of applying waste heat recovery technology. The waste heat sources that are characterized by medium or high temperatures are considered more economically feasible and practical for power generation. The ZHENIT technologies that can produce electric power from medium to high temperatures are Turbo-compounding (PTG, STG, Combined ST-PT), steam Rankine cycles, and thermoelectric generation. While there are other technologies that can lower the limit of waste heat temperature such as organic Rankine cycles, Kalina cycles, and Isobaric Expansion Engines that can produce power from low-medium temperature.

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Furthermore, as alternate power cycles develop, production at lower temperatures will eventually be economically feasible. Table 2.1 summarizes ZHENIT WHR technologies that can produce power from waste heat with some characteristics such as their temperature range, recovery source, capacity, efficiency, and specific cost.

Table 2.1: Summary of WH-to-power technologies

Technology	Temperature range	Recovery source	Engine size applicability	Capacity	Performance	Cost
Organic Rankine cycle (ORC)	Low - Medium	Exh. Gas / Jack. Wtr	> 250 kW	10 - 10,000 kW	η = 5 - 25%	1,000 - 100,000 €/kW
Isobaric Expansion Engines (IEE)	Low	Jack. Wtr /Charge air/ Exh. gas recirculation		1 - 1,000 kW	η = 1 - 14%	500 - 2,500 €/kW
Turbocompounding	Medium - High	Exhaust Gas	PTG < 15,000 kW STG < 25,000 kW ST-PT > 25,000 kW	500 - 10,000 kW	η = 3 - 15%	100 - 500 €/kW
Steam Rankine cycles (SRC)	Medium - High	Exhaust Gas	> 15,000 kW	500 - 20,000 kW	η = 3 - 20%	1,000 - 3,500 €/kW
Thermoelectric Generation (TEG)	Medium - High	Exhaust gas Jacket water		1 - 80 W	η = 1 - 20%	1,000 - 15,000 €/kW
Organic Flash Cycles (OFC)	Low - Medium	Exhaust gas Jacket water		5 - 200 kW	η = 5 - 20%	2,000 - 12,000 €/kW
Kalina cycles (KC)	Low - Medium	Exhaust gas Jacket water		20 - 100,000 kW	η = 7.5 - 35%	1,000 - 3,000 €/kW

The first WH to power technology is the organic Rankine cycle (ORC) which uses an organic medium on the same principle of steam Rankine cycles, the utilization of organic fluids gives the advantageous to

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recover low-temperature waste heat from jacket water and charge air. ORC is considered advantageous in terms of the efficiency and simplicity of the system. Moreover, it has the ability to recover waste heat from the engine's flue gas by integrating an exhaust bypass into the system and an economizer for heat capturing. The efficiency of ORC is ranged between 5-25% and the high efficiency is partly because it can generate power at lower load factors from the main engine.

When comparing the WH-to-power technologies with each other, it can be found that the Kalina cycles are probably not advantageous for maritime applications in comparison to ORC. Kalina cycles are complicated systems that require larger heat exchangers with high cost and require much high pressure while compactness and system simplicity are major requirements for maritime applications.

Organic Flash Cycles (OFC) belong to the same class of WHR technology as ORCs, i.e., power generation cycles where a liquid flow is turned to gas by a heat source before expansion in a turbine. Electrical power outputs from OFC in the range of 5 – 200 kW can be expected using heat sources with power approximately 100 to 2000 kW and with temperatures between 120°C and 200°C.

Thermoelectric generators (TEG) are devices based on solid-state semiconductors designed to convert thermal power into electrical power. A set of thermoelectric modules are arranged between two heat exchangers, with each thermoelectric module being composed of up to hundreds of thermoelectric pairs (electrically in series and thermally in parallel). TEG belongs to medium-high temperature, there are some designs made specifically for the recovery of heat from flue gases from on-board waste incinerators that operate at a temperature range of 850-1200°C. Furthermore, it is considered a type of onboard waste and pollution management device. All the available TEG modules in the market cost between 10 € and 70 €, for absolute power outputs in the range of 1 W to 80 W. For TEG modules above 5 kW_e/m^2, the specific cost can be expected in the range of 0 – 4,000 €/kW_e.

A power turbine generator (PTG) installed in the exhaust pipe bypass is the simplest device for turning engine exhaust into electricity. An effective approach to utilize engine waste heat is to place a power turbine in the main engine exhaust stream. Turbochargers require a very little amount of exhaust gas energy to operate. PTGs are suitable for a total main engine power below 15,000 kW and are the cheapest and smallest option for turbo-compounding systems since the only components needed are the power turbine and a new exhaust gas line. There is another turbo-compounding technology that uses the Rankine steam process cycle to produce electricity called a steam turbine generator (STG). To run the STG, bypassed exhaust gases are mixed with exhaust gas exiting the turbocharger train, to increase the temperature of the exhaust gas flow (+50°C approx.). While running at 100% SMCR, the STG system can be expected to produce electrical power equivalent to between 5% and 8% SMCR. While

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running at 100% SMCR, the STG system can be expected to produce electrical power equivalent to between 5% and 8% SMCR.

The third and most complex turbo-compounding system consists in a combined Steam Turbine, Power Turbine, and Generator (ST-PT). In the usual configuration, the power turbine is connected to the generator via a gearbox, with the steam turbine further connected to the same generator by another gearbox, all on the same shaft, with the exhaust gases first being used to produce steam in a dual-pressure exhaust gas boiler, then expanding through the power turbine. This solution can be used for marine systems with high electrical power demand. While running at a specified maximum continuous rating (SMCR), the ST-PT system can be expected to produce electrical power equivalent to approximately 10% SMCR. Combined ST-PT systems are suitable for main engine power above 25,000 kW.

Since the vaporization temperature of an organic working fluid is substantially lower than that of water, the steam Rankine cycle may be linked with an ORC process. The steam's condensing temperature is high enough to cause the ORC cycle's working fluid to evaporate. Because of the large increase in overall heat recovery to mechanical power, heat rejection temperature is reduced, increasing process efficiency.

2.1.2 WH-to-Storage

The waste heat onboard ships can be captured, transported and stored to be used later for several purposes. This scenario helps to increase the sustainability of energy use and reduce operational costs. Storing waste heat and turning it to power by using thermal storage systems is the link towards a better solution, enabling constant electricity production using WHR technology from waste heat. Thermal energy storage (TES) is a technology designed to resolve the mismatch between the availability of thermal energy at a certain heat source, and the heat demand elsewhere by storing the heat for later use. Time discrepancy between the supply and demand for heat is a non-negligible source of system-level inefficiency.

The ships have different operational profiles and their waste heat has intermittency characteristics, therefore, the storage scenario is the best way to prevent waste heat from being lost as without storage, the waste heat is limited to be used to the immediate heat demand. For example, the cruise ship is sailing at full speed and there is much more waste heat generated from the heat sources onboard and the generated waste heat is more than what is needed onboard. On the other hand, the same cruise

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ship is in port and there is a need for power for hotelling services such as the electric boiler. The solution for this is storing waste heat generated in sailing to be used in port instead of the oil boiler or the shore power to reduce fuel consumption and ship emissions.

Thermal energy storage (TES) is the obvious solution to smooth out the fluctuation of the engine thermal losses and make a match between the time profiles of available waste heat and of the onboard energy demand. Applications of TES can have a significant positive impact on the maritime sector as It is characterized by its energy-intensive procedures. Due to the large temperature operating range in storage mediums, TES technologies can permit its wider electrification.

There are three groups of TES each based on their own physical phenomenon and their operation principle: sensible thermal energy storage (STES), latent thermal energy storage (LTES), and thermochemical energy storage (TCS) .

STES is considered the most commercially deployed type of TES and features some of the cheapest and simplest designs. It relies on storing the thermal energy by heating or cooling the storage medium (solid or liquid) without effected its phase. it is considered the most mature TES technology (TRL ~ 7 - 8) and can be performed with a wide range of materials that cover a broad temperature range. The efficiency of STES to store the waste heat depends on the operating temperature range and thermal capacity of the storage medium. There are several STES technologies and the selection between them depends on the temperature level of the application. These technologies can be based on water as a medium or solid material such as ceramic bricks, rocks, concrete, and packed beds. Moreover, there are other technologies using inorganic chemical compounds such as molten salts. The water-based STES is considered the best technology for storing low heat within an operating temperature of 0-100 °C, while Molten salts TES is used for medium temperature heat storage (100 – 300 °C). The main disadvantages of STES are their large physical footprint, the fluctuating power output during discharge, and heat losses which limit storage duration and enforce good insulation.

LTES leverages the phase change enthalpy during a phase transition of a so-called phase-change material (PCM). It combines a good technology readiness level (TRL~ 6 to 8), energy storage density (100 - 300 kWh/m^3), and a wide variety of potential materials suited to different temperature ranges [1]. The selection of a PCM depends on the temperature range of the application and the thermal conductivity. The PCM technologies are divided into sub-zero suited for a temperature range below 0°C, low-temperature PCM suited for a temperature range between 0-120 °C, and high-temperature PCM that is applied to a temperature range above 120 °C. For low-temperature PCM, paraffin waxes and inorganic salt hydrates are considered the most commonly used. Inorganic salts such as molten

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carbonates, nitrate salts, and sulfate salts of alkali and alkaline metals are the most commonly used for high-temperature PCMs. There are differences in heat of fusion and temperature range for the melting points between the PCMs as shown in Figure 1.

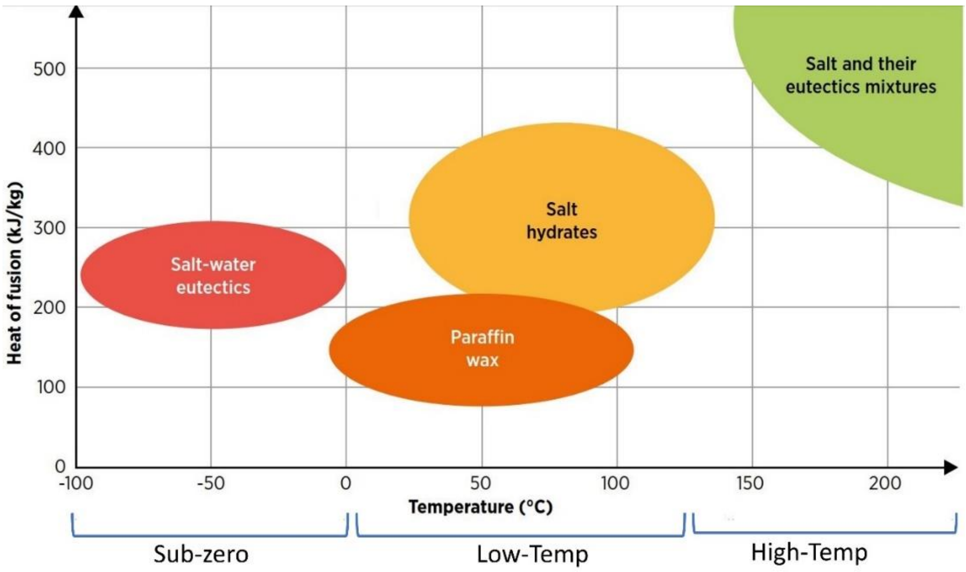

Figure 1 Properties of PCMs in terms of fusion heat and melting points temperature

TCS is characterized by higher energy density than STES and LTES and relies on the enthalpy of reaction of reversible endo/exothermic reactions [2]. TCS includes two different methods, reversible-reaction based and sorption-based, each of them divided into different methods as shown in Figure 2 [3], [4]. Reversible-reaction-based is characheristized by generating a high amount of energy as a result of an exothermic synthesis reaction, therefore, it can operate at higher temperatures. While Sorption based system can operate at medium temperature until 350 °C.

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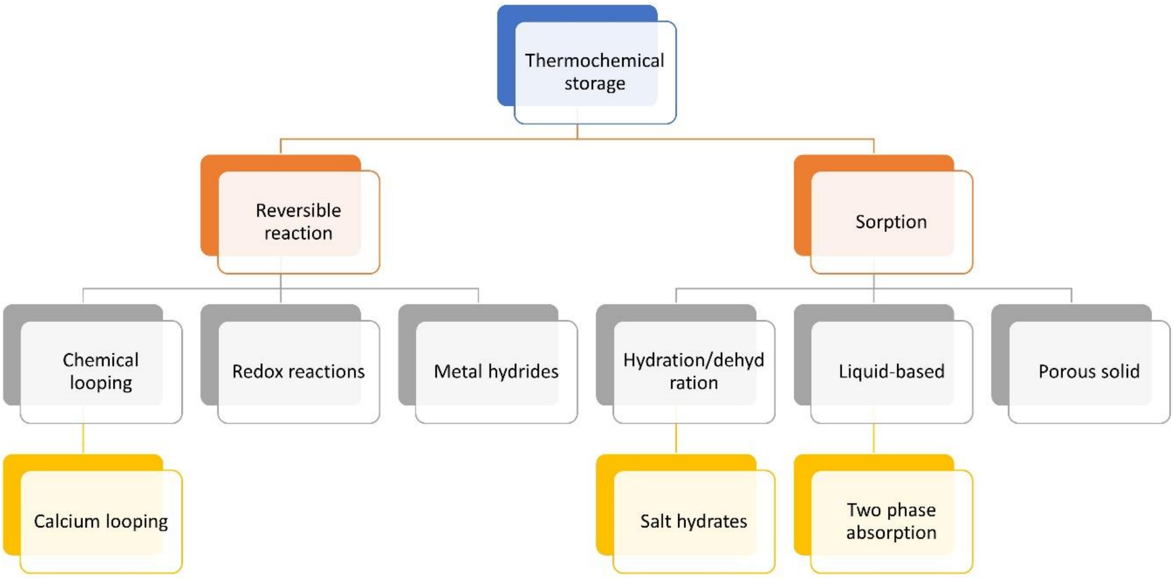

Figure 2 Thermochemical storage methods and materials

TCS is at an early development stage and still displays too many technical barriers for demanding applications such as WHR. The main limitations of TCS are a low technological maturity which translates into very few commercially available devices, with most working prototypes currently at the lab / bench top scale, and some system complexity associated with having to transport both heat and mass in/out of the TCS device. Thus STES and LTES are suitable TES candidates for on-board waste heat recovery.

2.1.3 WH-to-Upgrade

On onboard ships, one of the main waste heat available is the low grade heat sources that is considered hard to be recovered. However, the exploitation of a fraction of low-grade heat has a significant potential to improve energy efficiency and reduce fuel consumption, emissions, and operational costs. The solution for benefiting from these low-temperature heat is to upgrade them to a higher grade of heat. The special heat pumps can be used to generate higher grade of heat approximately 100 °C from waste heat at 45 °C.

The first technology that can be used is the mechanically driven vapour compression heat pumps which able to create a rise in the temperature with consuming a significant electrical energy to drive their

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compressors. Moreover, Vapor compression heat pumps lack suitable working fluids, therefore, many researchs have been done to overcome these limitations. For example, there is a research work that investigated ecofriendly working fluids to increase the low grade heat from 50 °C to about 130 °C, they found that the ethanol can be a good candidate for the single stage cycle while it has less efficiency potential for multi stage cycles [5]. On the other hand, two stage cycle has been investigated in [6] by using hydrocarbon fluids through a simulation in a numerical software and testing on the lab. They found that the upgrading of low-grade heat (about 30 °C) to a high-grade heat (115 °C) is possible with a COP equal to 2.

In contrast, the thermally driven heat transfomers can achieve this target of heat upgrading by degrading a fraction of the low-grade heat source without the need of high temperature source and by using negligible electrcity. The heat transformers are divided into three different types as found on the literature: Absorbtion heat transformers, thermochemical heat transformers and adsorption heat transformers.

Based on the literature [7]–[9], the thermochemical heat transformers can raise the temperature of heat source by about 16 - 85 °C with COP = 0.48 based on an experimental done on a prototype and on an operating temperature equal to 100 °C. But there are some limitations to this concept that prevent their widespread implementation such as sluggish chemical kinetics, poor gaseous permeabilities, and unrealible working pairs [10].

Similarly, the absorption heat transformers have the ability to raise the temperature by about 8-70 °C with COP=0.15-0.5 through the utilization of exothermic absorption which has been validated by experiment campaigns [11]and industrial prototype [12]. Its limitations are due to the use of toxic working pairs that can react with the working fluids. On the other hand, adsorption heat transformers has the advantage over the previous two types because they emply ecofriendly working pairs that are non toxic, have great material stability and have favourable reaction kinetics [13]. For example, an experimental compaign has been demonstarted to generate steam through using open adsorption heat transformer, they reported that COP equal to 0.31 and raise in temperature reached up to 100 °C [14]. The steady-state results in [15] indicate that up to 49% of the low-grade waste heat might be raised to the appropriate high-grade heat.

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2.1.4 WH-to-Direct End-Use

There are some thermal end uses onboard ships that can benefit from the installation of WHR systems as the heat can be used for heating fuel, domestic hot water, space heating, cargo heating, cooling, and refrigeration. Most of them can benefit from low-temperature heat sources (<200 °C) to reduce the energy consumption onboard ships and reduce the emitted emissions.

The waste heat can be used to improve the energy efficiency of the heating or cooling process in a cost-effective manner. This can be done by direct re-use of the thermal energy available in the waste heat such as preheating combustion air, hot water feeds, space heating, and water preheating. The equipment that can be used as a tool to apply the waste heat to direct end-use scenarios can be heat exchangers, regenerative burners, economizers, waste heat boilers, waste heat steam generators, heat pipe systems, heat pumps, etc.

For example, heat pumps are used for heating or cooling processes by extracting the waste heat and delivering it to the space that needs to be heated or cooled. An economizer can be used to recover the low-temperature or medium-temperature waste heat to the heat liquids. Regenerative burners can be used for direct waste heat recovery scenarios by preheating the air used in the combustion process of diesel engines installed onboard ships. They are designed to recover the heat by using the concept of the counter-flow system between the supply and the demand streams. Heat pipes are considered thermal conductors that can make the transmission of heat and keep It at a constant temperature over a lengthy distance. One of the advantages of heat pipes is the missing moving parts, therefore, they are considered reliable devices. Moreover, their lifetime is more than 20 years. Heat pipes can be used for upgrading heat from a lower heat grade to a higher one or used directly to be an energy source for cooling scenarios such as absorption cooling systems.

Furthermore, the waste heat can be used to directly generate electricity without producing mechanical power. The technologies that were developed to conduct this conversion are thermoelectric generators, thermionics, and piezoelectric devices. Thermoelectric generators are based on the Seebeck effect and contain semiconductor solids that permit the direct generation of electricity when subjected to a temperature difference between the heat source and heat sink. This technology is limited because of its low efficiency and high cost. The piezoelectric devices can convert the low heat grade waste heat into electricity directly. The piezoelectric devices are characterized by high internal impedance, complex oscillatory fluid dynamics, high costs, and low efficiency.

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2.1.5 WH-to-Cooling

Recovering waste heat onboard ships to cooling capacity is required independent of the vessel type. Refrigeration represents high demanding application onboard ships, especially in emissions reduction and energy efficiency improvement. While most cooling power generation machinery is electrically powered, recent research has been motivated by the search for energy-efficient heat-driven refrigeration systems. In ZHENIT technologies, two options can be used to produce cooling, Sorption refrigeration & desalination and Absorption refrigeration.

Sorption is considered a reversible thermochemical reaction in a hybrid system that generates cold power and clean water. Sorption technology is considered a promising way to preserve food onboard ships as it saves the cooling power required with a reduction of fuel consumption and ship emissions. Sorption refrigeration lever the low evaporation temperature at the low partial pressure of a refrigerant. Heat can be removed from a heat transfer fluid to evaporate this refrigerant and bring the heat transfer fluid down to low temperatures (-2°C to 5°C), which is the intended cooling effect of the cycle. The temperature of the generated cold stream depends on the evaporation temperature at a low partial pressure of the refrigerant. Based on the literature review, the application of Sorption technology has been studied for the naval sector for heat recovery, space cooling, space heating, ice making, and refrigeration applications.

On the other hand, absorption refrigeration technology is one of the effective options to convert waste heat onboard ships into cooling power. One of the main advantages of absorption refrigeration is that the process of pumping the working solution that has absorbed the refrigerant requires significantly less work than compressing the equivalent vapor in the vapor-compression system, due to the lower specific volume of the liquid solution [11]. In general, there are two types of absorption refrigeration, lithium-bromide-based and the ammonia–water-based. One of the differences between them is the lowest temperature that can be reached, lithium-bromide is remain above zero while ammonia–water can reach -30 °C. Therefore, the ammonia–water-based absorption refrigeration system is considered more competitive for marine cryogenic refrigeration, particularly for fishing ship refrigeration as it is suited to lower temperatures.

2.1.6 WH-to-Freshwater

The freshwater availability onboard ships have a crucial concern to all ship operators and marine stakeholders. Maritime applications have an advantage compared to other applications in terms of the

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availability of good sources of fresh water if desalination processes are employed in the seawater. The desalination technique is classified into thermal and membrane processes, thermal one requires heat energy to evaporate the saline water while membrane processes require high pressure like what happened in Reverse Osmosis. Therefore, the waste heat from marine engines can be used to provide the required energy for desalination processes.

Thermal desalination processes include some systems that are already carried out onboard ships such as multi-effect desalination (MED) and multi-stage flashing (MSF). Membrane distillation (MD) relies on a partial pressure differential across a hydrophobic membrane, therefore, it requires lower heat/pressure than other desalination processes [16]. The method uses low-grade waste heat, such as the water used for an engine cooling system onboard a ship to produce freshwater by combining heat and mass transfer across the membrane.

Waste heat evaporators are considered a good way to produce freshwater onboard ships by using flue gas, steam, and jacket water cooling. The source of distillation can be seawater, brackish water, or contaminated feed water. Heat recovery evaporators (HRE) such as this one (Figure 3) offer a weight reduction, has a small footprint, and require no replacement parts. Therefore, they can be used onboard several types of ships such as tankers, cargo vessels, offshore supply vessels, and military vessels such as submarines, aircraft carriers, and, destroyers [17].

Figure 3 Heat recovery evaporator [17].

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HRE systems are superior to conventional desalination systems for a variety of reasons. The most energy-efficient desalination process is heat recovery evaporation. The process uses waste heat, which is typically released into the atmosphere, to meet most of its energy needs. Because it is not necessary to haul big tanks of drinkable water or bottled water, fuel efficiency on ships is increased. When significant amounts of water are not required to be stored, there is also more cargo space available. The operation of HRE in a vacuum at low boiling temperatures reduces the amount of maintenance required for cleaning and scaling the heat transfer surfaces. There are no hydraulic parts that operate at high pressures (700–1,000 psi), therefore, it requires less maintenance compared to other systems. HREs are dependable because of low-pressure systems, fewer moving parts, and straightforward designs.

2.2 Integration of technology scenarios

To obtain an improved performance and output power from the waste heat sources available onboard ships, it is recommended to integrate WHR systems to achieve energy and cost-efficient zero WH. There were some efforts in the literature have been made toward the integration of different waste heat recovery technologies.

The first possible integration is between two WHR technologies from WH- to power scenario to improve the energy efficiency and extract more output electrical power. There are some efforts in the integration of the organic Rankine cycle and Kalina cycles as presented in [18] where the authors propose the integration of ORC and Kalina cycle in a combined WHR system by using the exhaust gas and jacket water waste heat from a combined heat and power engine as shown in Figure 4. The study examined the optimal values of different parameters to be used for Kalina cycles. Moreover, the study's results concluded that the net power output from the combined WHR system was equal 211 kW (divided into 168.69 kW for KC and 42.34 kW for ORC) with thermal efficiency equal to 26.5% and the payback period is 4.2 years.

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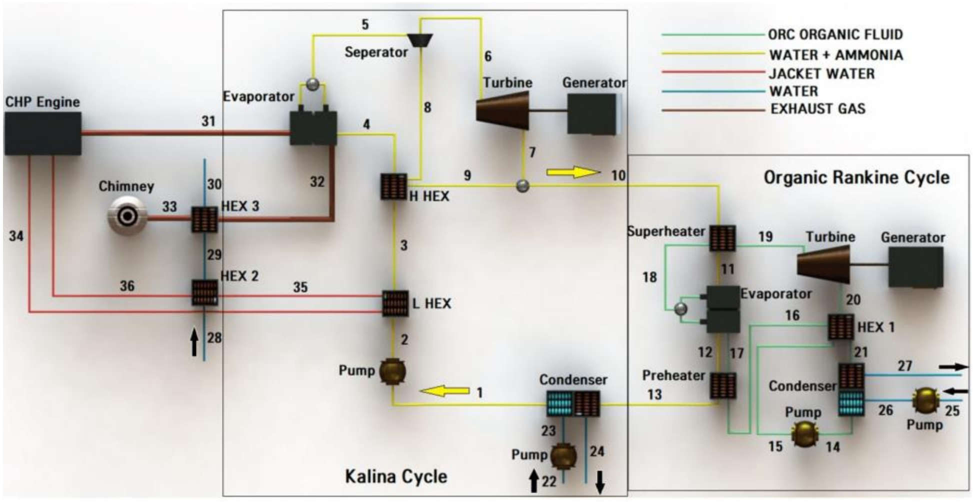

Figure 4 Combined cogeneration cycle including KC and ORC for recovering waste heat of exhaust gas and jacket water of the engine [18]

Moreover, there is another contribution [19], the authors conducted an experimental campaign to study the integration between ORC and KC in a combined WHR system from an Internal combustion engine and examine this integration from energy balance and exergy analysis perspectives. They employed ORC to recover the waste heat available in the exhaust gas and lubricant oil, while KC is employed to recover the waste heat of jacket water cooling as shown in Figure 5. The results of the study found that the network of the combined WHR system is 261.52 kW (216.24 kW for KC and 45.28 kW for ORC) with a thermal efficiency of 16.51%.

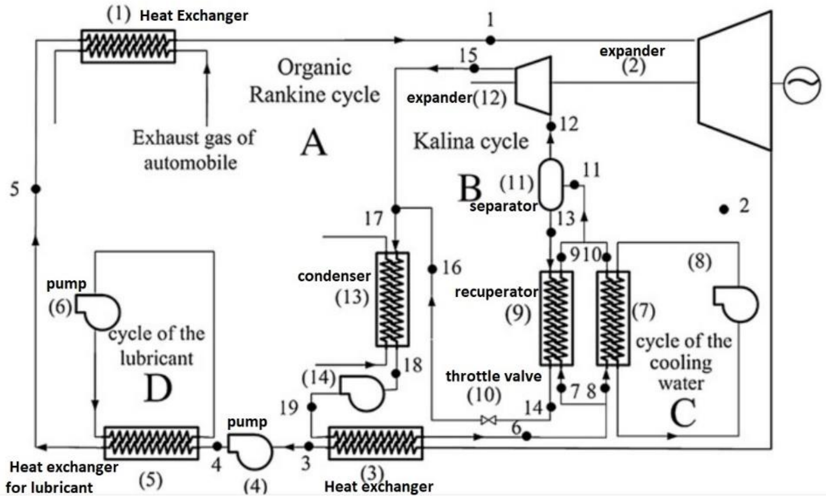

Figure 5. System diagram of the combined ORC and KC cycles for waste heat recovery of ICE [19]

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Furthermore, the ORC can be integrated with a Steam Rankine cycle (SRC) and power turbine (PT) to generate more power by using the waste heat available in marine low-speed diesel engines as shown in[20]. The study proposed the utilization of exhaust gas of diesel engines as a high-temperature heat source to power the power turbine and the installed turbocharger in the diesel engine. After that, the two streams of exhaust gases pass through waste heat boiler to produce the required steam for SRC and hot water for the evaporation process inside the ORC as shown in Figure 6. Moreover, the jacket water cooling is used to preheat the feedwater of SRC through a heat exchanger. While the scavenge air from the diesel engine is used to preheat the feedwater. The study results showed the ability to generate up to 1079 kW at 100% load with a thermal efficiency equal to 28.5%. Additionally, the payback period is evaluated to be 5.2 years for the proposed combined WHR system.

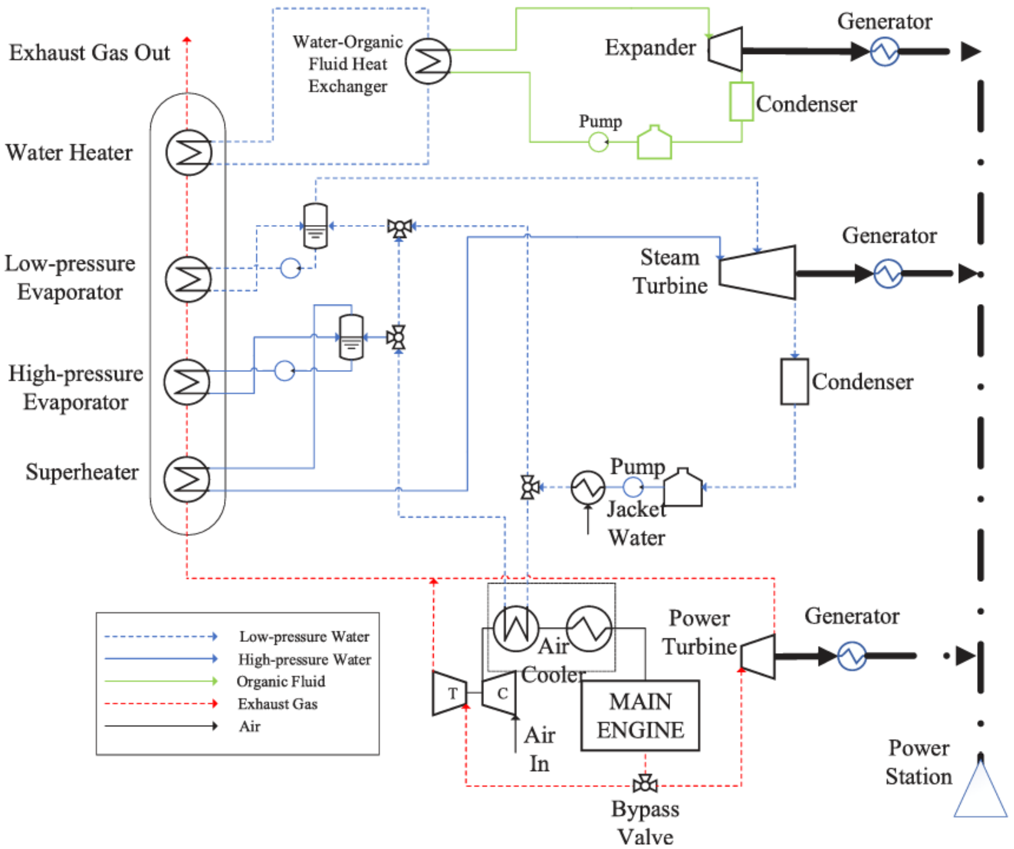

Figure 6. System diagram of the combined ORC, SRC, and PT for waste heat recovery of marine diesel engine [20].

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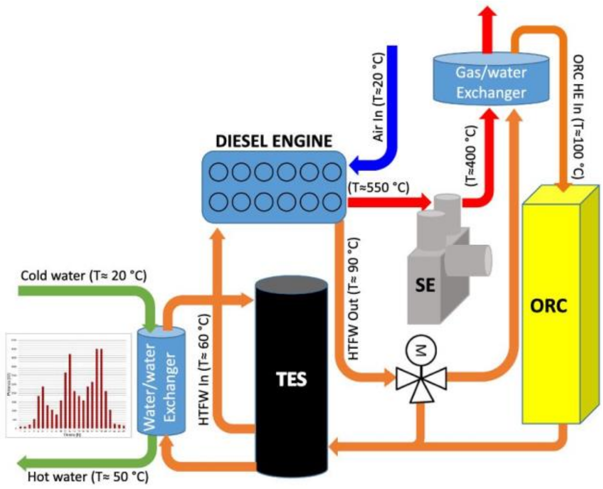
One of the challenges and limitations that face the application of WHR systems onboard ships is the fluctuations of power and temperature that depend on the operational profile of the ship. Therefore, the integration of Thermal Energy storage as a WH-to-storage technology with another technology from WH-to power such as ORC can be considered a solution to improve the WHR performance and overcome the problem of power fluctuations. Furthermore, this integration will permit the storing of waste heat excessed during sailing operations to be employed in port to cover the heating demand instead of using boilers and reduce fuel consumption. Therefore, the study on [21] proposes the integration of TES with ORC and Stirling engine in a combined WHR system for maritime applications. There is a small-scale prototype has been built and tested in an experimental lab under the operational conditions of cruise ship including the simulation of operational modes such as sailing, manoeuvering and berthing at port. The results of the study proved the ability to generate the required hot water during sailing by recovering the waste heat into the proposed combined system instead of using the boilers.



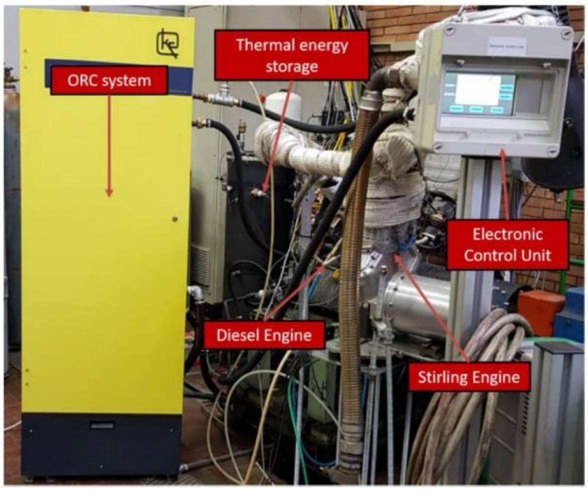


Figure 7 . Schematic of the combined WHR system and the prototype layout [21]

There is another possibility to integrate WH- to upgrade and WH-to Freshwater technology scenarios with each other to enhance the performance of WHR as shown in [22]. The paper developed a hybrid WHR system between the Adsorption Heat Transformer (AHT) and Multi-effect distillation (MED) to upgrade the waste heat from low heat grade to higher one through the adsorption process and improve the performance of desalination. Figure 8 descibes the process of the hybrid system, there is one waste

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heat source required to be supplied to the AHT to be upgraded to high grade heat. Thus, the upgraded adsorption heat is supplied to evaporate the sea water inside the MED system. The usage of a single low-temperature heat source is considered advantageous to the proposed system over the existing standalone technologies. The hybridization lead to a higher water production rate, almost twice the water production rate of standalone MED system , while the performance ratio has been improved from 4.2 to 5.4. The improvement in the performance ratio and the water production rate is because of the extension in temperature difference between the Top and Bottom Brine Temperature which permits the MED to adapt extra effects with a fixed temperature.

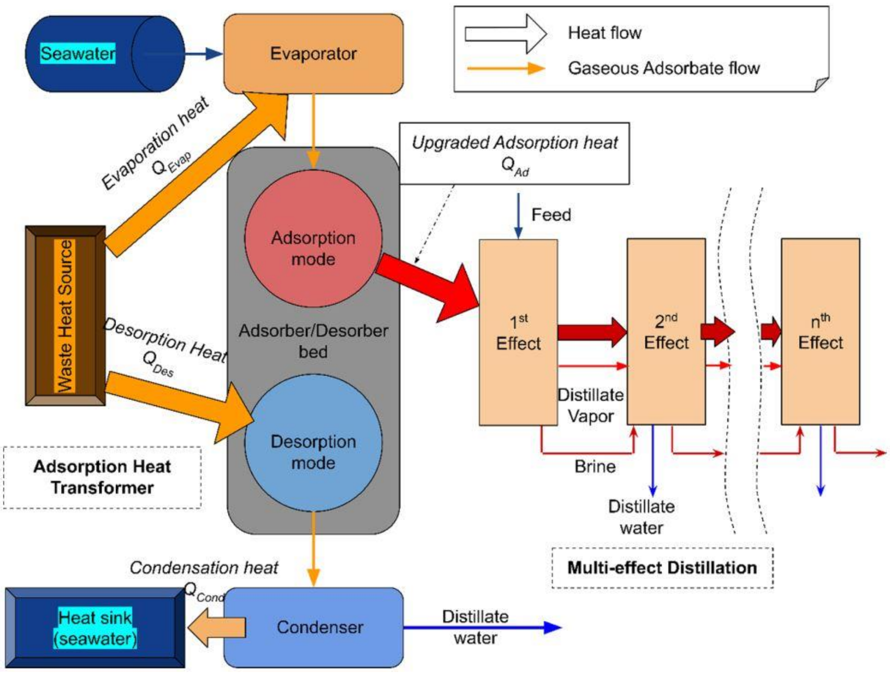

Figure 8 . Process description of the AHT + MED system [22].

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3 Market and boundary conditions

This section aims at presenting the market and boundary conditions evaluated as relevant for the implementation of the technical solutions described in Section 2 onboard different categories of vessels.

3.1 Cost-effectiveness of WHR system

Installing a WHR system onboard ship entails several expenses that are mostly independent of the ship type and its size. The total cost of the installation of a WHR system onboard ship includes the capital expenses (CAPEX) of the WHR system and the operational expenses (OPEX), for example, the maintenance costs that repeated year for the different components of the system such as boiler, turbine, pump, heat exchanger, condenser, etc. Based on the literature review, the CAPEX of installing a WHR system onboard a ship is anticipated to range from € 5 million to € 9.5 million based on the size of the WHR system. The specific cost (expressed in €/kW) for the investigated WHR technologies in ZHENIT project divided into minimum and maximum factors is shown in Figure 9.

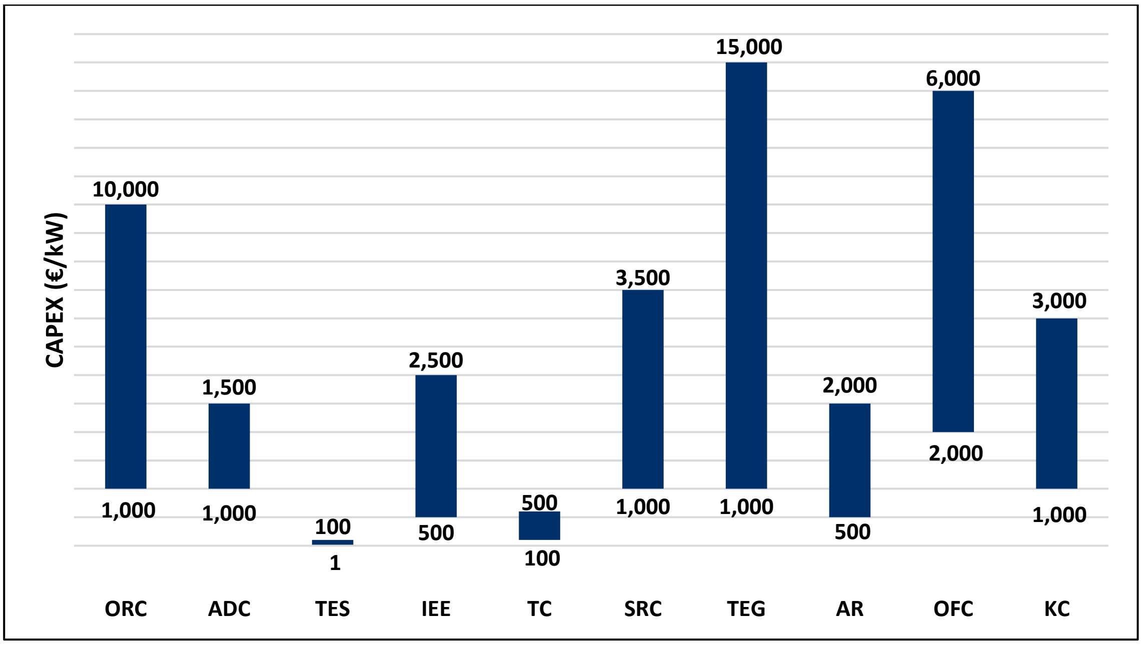

Figure 9 Specific cost of the investigated WHR technologies (€/kW)

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While the OPEX is based on the type of WHR system, for example, the maintenance costs for power turbine generator (PTG), steam turbine generator (STG), and combined ST-PT generator are estimated to be €10,500, €21,000, and €32,000, respectively [23].

On the other hand, the benefit of installing a WHR system onboard ship is that it will result in generating more electrical power that can be used for auxiliary systems or hotelling services and hence reducing the fuel consumption onboard. The annual savings of applying the WHR system onboard ship in terms of savings in fuel consumption can be calculated by multiplying the expected fuel consumption in tons corresponding to the annual power output from the WHR system by the fuel cost as described in Eq. (1).

$$AS_{i,f} = P_{avg,i} * T_i * SFC_f * C_f * 10^{-3} \quad (1)$$

Where $P_{avg,i}$ is the average power output from the WHR system measured in kW, $T_i$is the number of operating hours of WHR onboard ship, SFC_f is the average specific fuel consumption from the installed maine engine onboard ship measured in kg/kWh and C_f is the fuel cost measured in €/tonne fuel. Moreover, the cost-effectiveness based on the annual savings in fuel consumption can be evaluated by dividing the annual savings value ($AS_{i,f}$) by the annual power output from the WHR system.

Furthermore, the annual saving in emitting CO_2 onboard ship resulting from applying WHR system ($AS_{i,f,CO2}$) can be evaluated by using the same formula in Eq. (1) and changing the parameter of fuel cost by conversion factor between tons of fuel burned and tons of CO_2 produced (CF_f), its value varies with the fuel type utilized onboard. Moreover, the annual savings can be assessed by applying the EU-Emission trading system (ETS) on the quantity of CO_2 that was predicted to be produced from the conventional system without the WHR system.

3.2 Installation aspects

The installation aspects of WHR onboard ships are one of the determining factors that must be taken into account when installing the system such as the system scale, and architecture of the piping connections between different components. Moreover, the location of WHR system components must be considered to be assembled close to the heat sources that already exist in the engine room. So the shipyard must save a suitable space onboard for the installation of the WHR system including its piping and fittings.

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The connection between WHR components with each other or with the heat sources onboard is considered the decisive aspect for categorizing the WHR installation to be simple or complex. For example, the Power Turbine and Generator (PTG) systems are connected to the heat source (main engine) by using the exhaust gas by-pass only, therefore, this WHR system is considered a simple installation. Moreover, PTG systems are considered the smallest option for turbo-compounding systems.

On the other hand, the Steam Turbine and Generator (STG) system requires more space to be installed onboard as it includes various components that should be linked together by using multiple pipes for delivering the exhaust gas from the heat source to the boiler, the generated steam from the boiler to the steam turbine and the condensed water from the condenser to the boiler to achieve the recirculation process. The condenser is considered one of the complex reasons for the STG system as it is recommended to be installed in a specific location relative to the steam turbine (under the bedplate) and having many pipelines for cooling water and the condensed water. Based on the available STG products, the condenser is considered as large as the turbine itself, therefore, its space in the engine room must be taken into account when installing STG onboard ship [24].

When installing WHR system especially the turbine-driven energy systems using engine exhaust gases onboard a newly built ship, the designers must provide a suitable area for the system components to be correctly arranged as shown in Figure 10 which shows an example of the container ship engine room arrangement by installing a turbo-compounding system by using engine exhaust gases.

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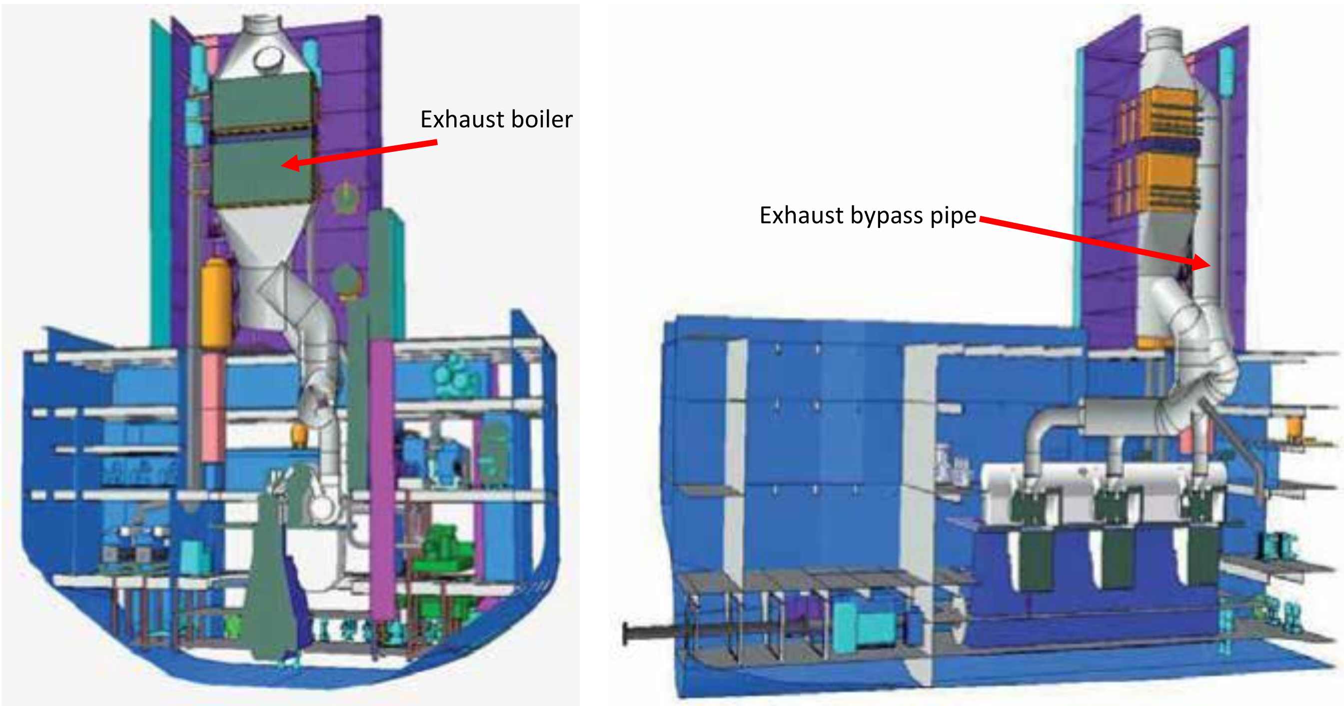

Figure 10 Container ship engine room and casing arrangement (left) transversal section, (right) horizontal section [24]

3.3 WHR system control

The control of the WHR system should be integrated with the control of the main engine as it generates power from the available waste heat inside it, moreover, WHR should be combined with the whole control system of the vessel. Therefore, the synergy between the control system depicted in Figure 11 is required.

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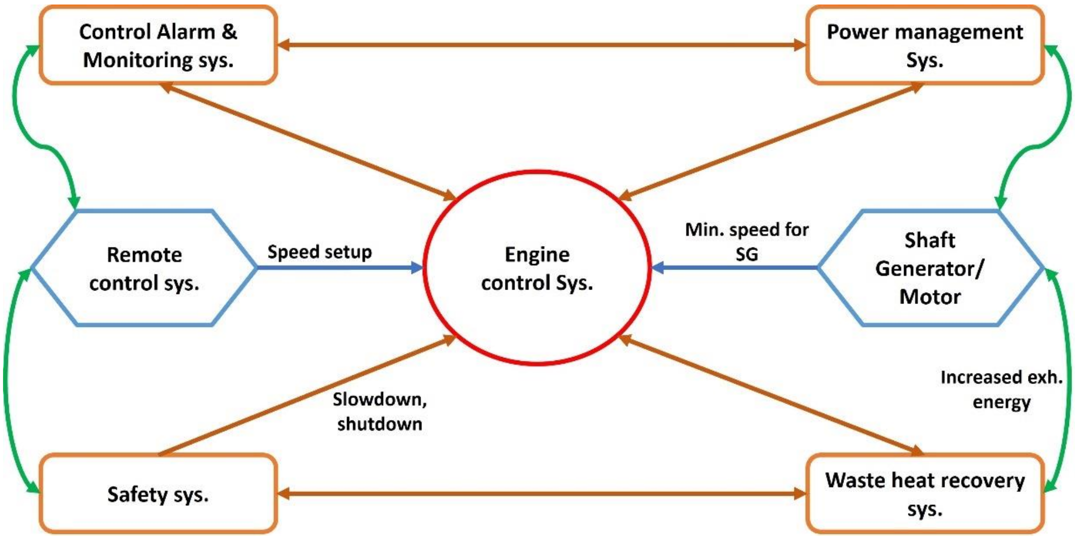

Figure 11 Ship control systems that are normally found onboard a large vessel

The integration of a control system between the WHR system and the main engine can optimise the utilization of fuel onboard the ship at various sailing conditions and reduce the operational costs, therefore, it is considered a crucial factor for the ship owner. As shown in Figure 11, the power management system is responsible to control the engine, alarm/monitoring and shaft generator or shaft motor. Moreover, the WHR system is affected by the dynamics of the engine so the planning of the control interfaces between them requires careful consideration.

When designing the integration between WHR system control and the main engine control, the target must be ensuring the protection of the engine from unacceptable conditions and providing the maximum available waste heat to the WHR system for recovering more power. For example, the optimum integration between the Combined steam turbine/power turbine system and the main engine onboard ship can be achieved by controlling the amount of heat by using an exhaust gas bypass (EGB) control valve as shown in Figure 12. The EGB control valve ensures delivering the suitable amount of exhaust gases to the WHR system within acceptable limits that protect the engine. There is another control valve available before the power turbine called the PT control valve that is responsible to control the amount of exhaust entering the power turbine, thereby, the generated power. Furthermore, the amount of exhaust delivered to the steam turbine and its output power is controlled by another control valve located between the exhaust boiler and the steam turbine.

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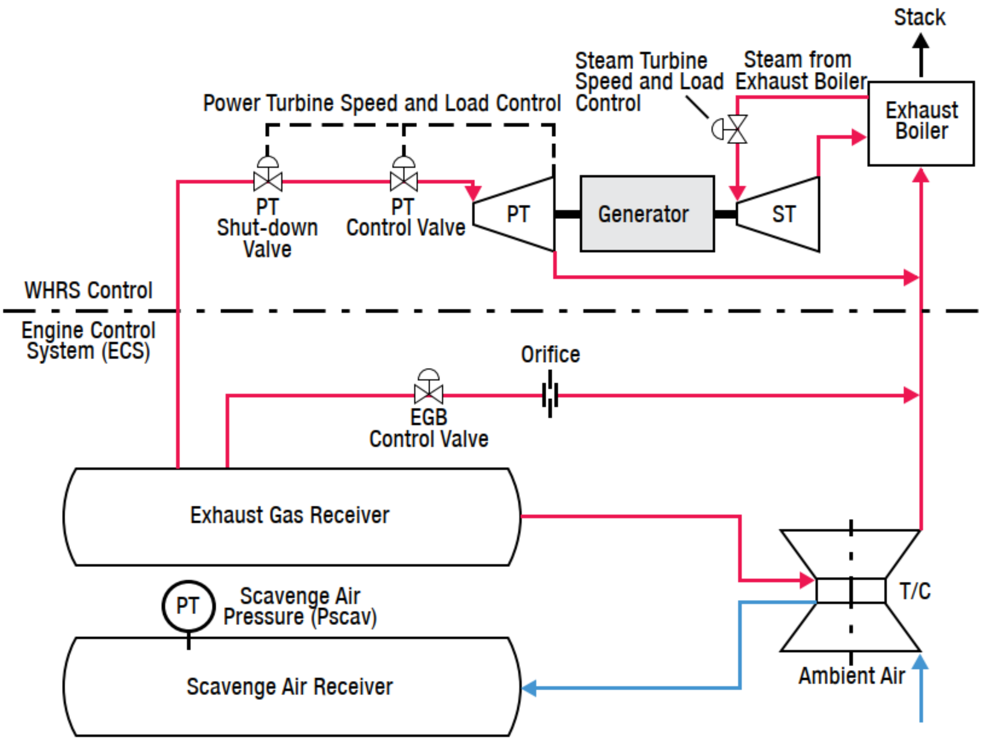

Figure 12 Control strategy of the Combined steam turbine/power turbine and generator (ST-PT) systems

3.4 Waste heat sources characteristics

3.4.1 Waste heat quality and temperature

An important consideration and boundary condition for WHR applications is the assessment of the heat quality, which is a measure of the waste heat's usefulness. The waste heat quality influences numerous WHR specifications, such as the system size, capital cost and performance. The availability of heat sources onboard ships like exhaust gas, jacket cooling water, lubrication oil, and charge air determines the potential output and performance of the WHR system. According to Table 3.1, opportunities for WHR can be broken down into three categories: low, medium, and high-quality based on the temperature ranges of waste heat sources [25].

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Table 3.1: Quality category and its corresponding temperature range [25].

Quality	Temperature range
Low	≤ 230°C
Medium	230°C < T < 650°C
High	≥ 650°C

As shown in Table 3.1, the categorization of heat quality depends on the waste heat temperature which also determines the feasibility of WHR. Ships have numerous heat sources with different temperature ranges as shown in Table 3.2 [26], [27]. Moreover, It is recommended to keep the output temperature of the exhaust gas after utilizing it in WHR such as ORC to be more than 160 °C for avoiding sulfur acid condensation.

Table 3.2: Temperature range of available heat sources onboard ships [26], [27]

Heat sources	Temperature (°C)
Incinerator	850 – 1250
Engine exhaust gas	200-500
Scavange air	100 – 160
Jacket cooling water	70 – 125
Lubricating oil	60

In general, the waste heat quality depends on the temperature difference between the heat source and the heat sink. From the basic equation of heat transfer that includes the overall heat transfer coefficient, heat exchanger area, and the temperature difference, there is an inverse relationship between the temperature difference and the required area as shown in Figure 13. As shown in Figure 13, at lower temperatures, there is a turning point where the area needed for the heat transfer drastically rises. Moreover, the overall heat transfer coefficient has an impact on the curve’s shape.

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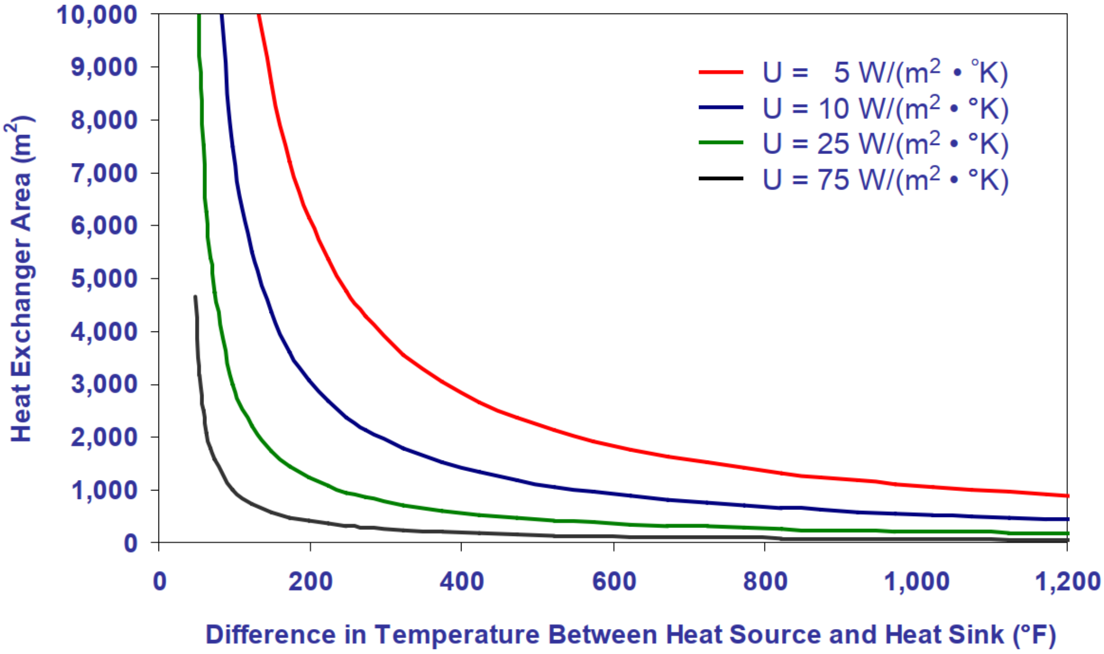

Figure 13 The Influence of Source and Sink Temperature (ΔT) on Required Heat Exchanger Area

In addition, the material selection of heat exchangers inside the WHR system is significantly affected by the temperature of the waste heat source. When heat source temperature rises greatly, it speeds up corrosion and oxidation processes, just like they do with other chemical reactions. The surfaces of WHR components can be seriously harmed if the waste heat stream contains corrosive materials. Some aspects must be followed when dealing with high-temperature waste heat, for example, it is recommended to use composite and advanced alloys material instead of carbon steel and stainless steel which oxidize at temperatures above 425 °C and 650 °C, respectively. Furthermore, ceramic materials are preferred to be used when dealing with waste heat sources of a temperature over 871 °C instead of metallic materials.

3.4.2 Waste stream composition

The waste stream chemical composition doesn't straightforwardly impact the waste heat quality or its amount, even though, it influences the material selection of the surfaces and the recovery technology. The effectiveness of heat transfer depends on the thermal conductivity and heat transfer coefficients that directly depend on the waste stream composition. Therefore, the waste stream composition will affect the design of heat exchangers and their material selection.

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Furthermore, the waste stream phase will influence the heat transfer rate. According to Table 3.3, the fluids with high density have a high heat transfer coefficient, therefore, the rate of heat transfer is increased by using these fluid types [28].

Table 3.3: General Range of Heat Transfer Coefficients for Sensible Heat Transfer in Tubular Exchanger [28]

Fluid Conditions	Heat Transfer Coefficient (W/(m^2 .°K)
Water, liquid	5×10^3 - 1×10^4
Light organics, liquid	1.5×10^3 - 2×10^3
Gas (P = 1,000 kPa)	2.5×10^2 - 4×10^2
Gas (P = 100-200 kPa)	8×10 - 1.2×10^2

The chemical reaction of substances in the waste heat stream with the materials of the heat exchanger is another important factor. Heat exchanger fouling is a prevalent issue that can significantly lower efficiency or lead to system failure. Heat transfer rates and fluid streams inside the heat exchanger can be impeded by substances deposited on the surface. In other instances, the heat exchanger will deteriorate to the point where it is no longer usable.

3.5 Ship operational profile

The ship's operational profile impacts the waste heat source performance from the engines, which has a significant impact on the viability of installing the WHR system. The ship in its normal service has many operational conditions such as sailing, maneuvering, berthing, and on anchor. Therefore, the profile of waste heat sources varies with the operational profile of the ship unlike the other WHR applications on land such as geothermal and biomass industry. Moreover, the number of operating days that the vessel sails per year is a crucial parameter that must be taken into account for taking the investment decision of installing a WHR system onboard ships because of its impacts in terms of return on investment.

The operational profile is complex and hard to be obtained, therefore, there are some strategies that can be used to express it. Utilization of a speed distribution histogram of the ship by evaluating the operating hours expressed in percentage from the total sailing time versus its corresponding sailing speed is considered the more typical approach to portray the operational profile of the ship. Figure 14 (a) shows the speed distribution histogram of container ships at sea in which sailing at several speeds ranged between 12 and 24 knots. On the other hand, Figure 14 (b) shows the speed histogram of

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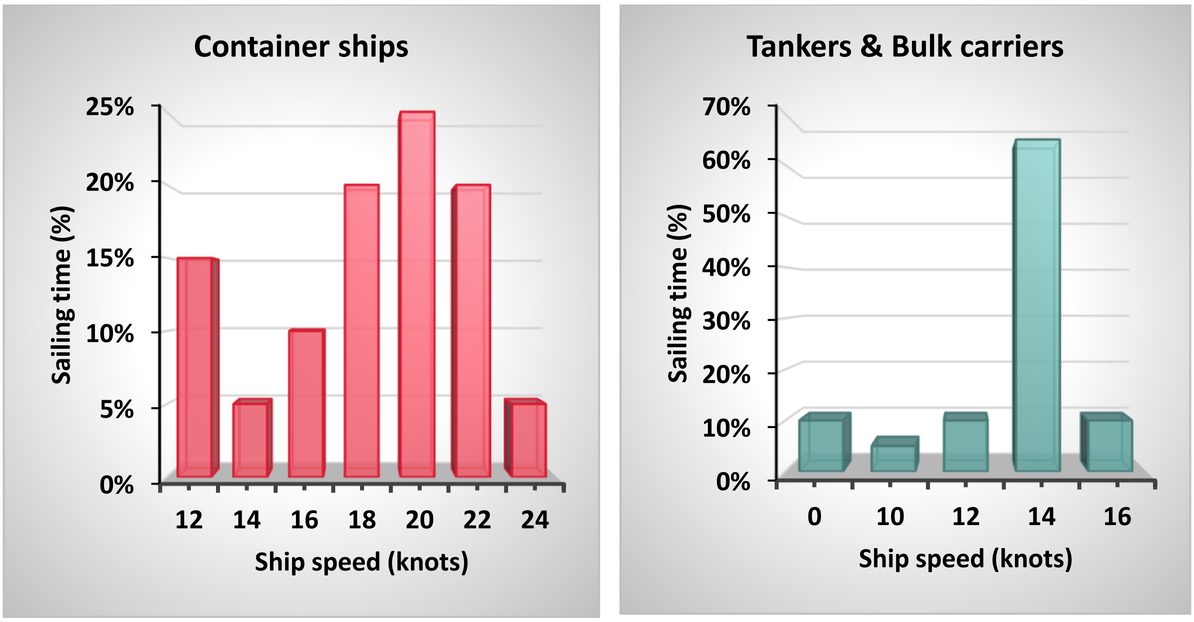
tankers/bulk carriers that mostly sail at a particular speed (in this case 14 knots). Consequently, the ship type influences the shape of the speed distribution histogram, thereby, impacting the operational profile of the ship.



(a) (b)

Figure 14 Typical operational profile for (a) Container ships, (b) Tankers & Bulk carriers

For another ship type such as the offshore supply vessel, it has a different operational profile which influences the quality, temperature, and amount of the waste heat sources from its engines. Its operational profile includes the following modes: transit from onshore to the offshore site (sailing) and vice versa, loading and unloading of cargo from the berth, loading and unloading cargo to the offshore platform by using a dynamic positioning system (DPS), loading waste from the rig and unloading it to the berth, and finally the standby mode.

Furthermore, the operational profile of the ship is considered one of the key elements in the evaluation of the payback time for the WHR system installation as discussed in [24]. To use the operational profile in the assessment of payback time for WHR systems, the sailing hours at each speed or the sailing under different operation modes must be converted to the corresponding engine load and its running hours. MAN Diesel & Turbo [24] conducted an example for selecting the best waste heat recovery system in terms of the payback time of investment onboard a container ship. The container ship 's capacity is

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14000 TEU and the ship is powered by a single main engine (MAN B&W11S90ME-C9.2), its specific maximum continuous rating (SMCR) equals 57,823 kW. The annual operating time on sea and harbor is 6,480 hours and 2,280 hours, respectively. The sailing speed was converted to the main engine load factor (% SMCR), therefore, Figure 15 shows the corresponding operating hours for each engine load and its percentage compared to the total sailing time (6,480 hours).

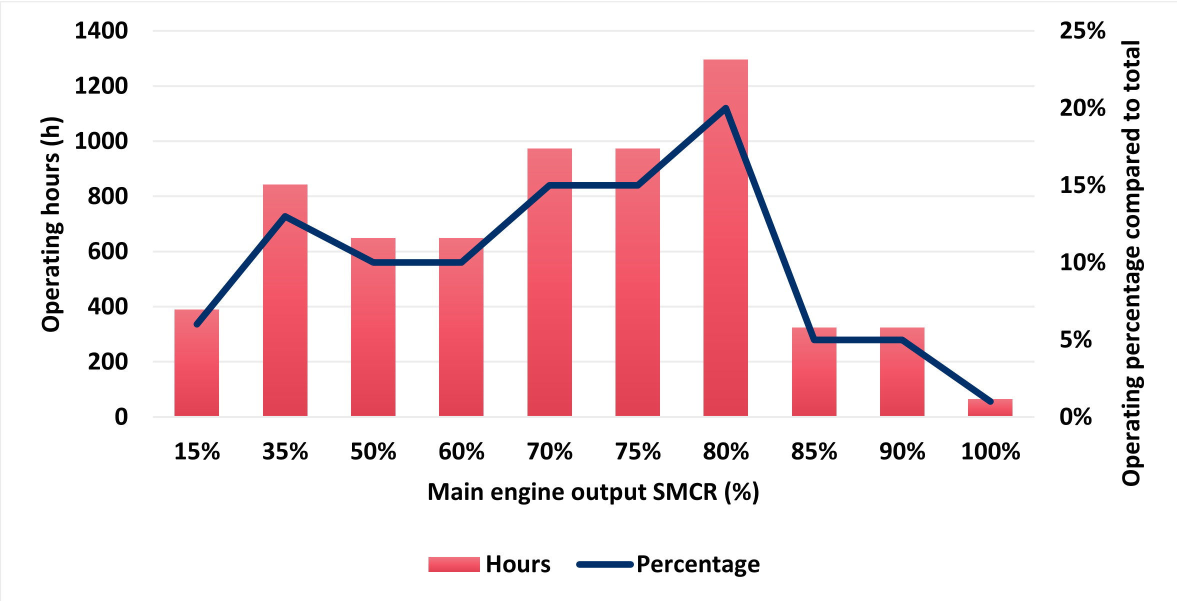

Figure 15 The main engine load vs. the operating hours of a large container ship

Based on the operational profile and the potential power output from three different WHR systems (PTG, STG, and combined ST-PT), the assessment of the corresponding payback time based on the net present value (NPV) and the cash flow has been shown in Figure 16 [24]. For achieving practical payback results, the study included an estimated value for the WHR systems installation on the shipyard and its commissioning costs.

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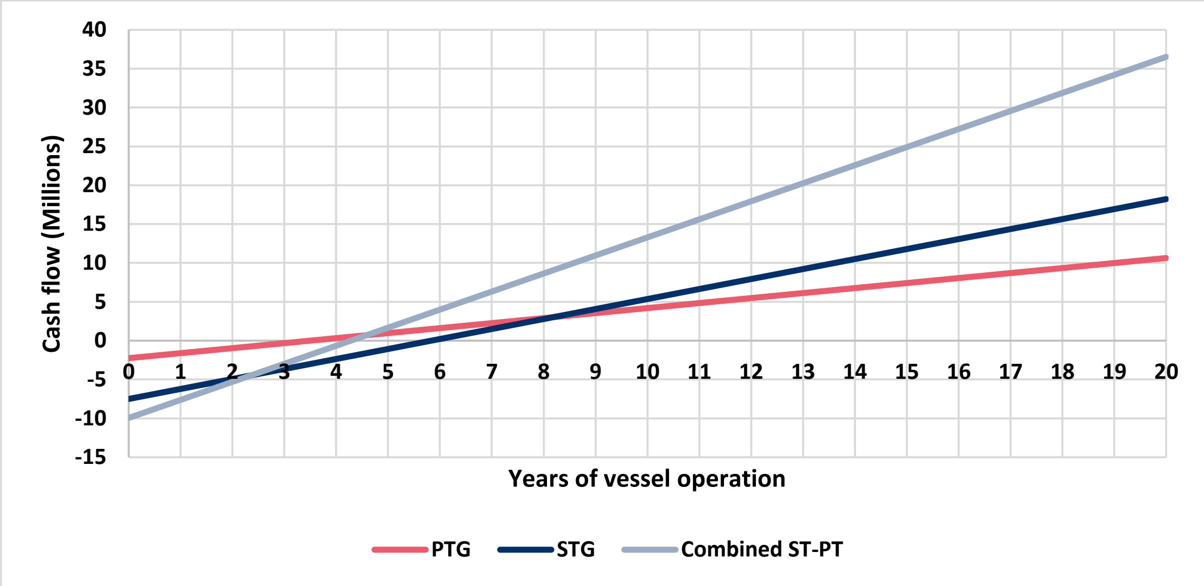

Figure 16 Container ship payback assessment for WHR systems based on the net present value calculation.

As shown in Figure 16, the payback time varies with the type of the WHR system as the payback time is 3.5, 5.8, and 4.3 years for PTG, STG, and combined ST-PT systems, respectively. The previous payback time can be reduced by increasing the operating hours in sailing more than the selected frame of 6,480 hours (74% per year). Moreover, the most interesting benefit for an owner is the fuel cost saving because of applying the WHR system over the ship's lifetime. As shown in Figure 16, the fuel cost savings from applying the combined ST-PT system for 20 years equal to USD 36 million which is considered two and three times the utilization of STG and PTG, respectively.

3.6 Specifications of engines onboard ships

The type of engine is considered one of the boundary conditons onboard ships that impacts the waste heat temperature and its mass flow. For example, the design of engine cooling system influences the flow and output temperature of cooling water that used as a heat source in WHR system. For 2 stroke marine engine, there are separate cooling streams that used to cool down the different components of the engine such as Jacket water cooling that operates at temperture range of 83-89 °C, scavange air that has an average temperature of 100 °C, and lubricating oil that normally operates at temperature below 60 °C. On the other hand, four-stroke marine engine, the cooling streams are divided into high temperature and low temperature cooling circuits.

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The high temperature cooling circuit provides the required cooling at a temperature range of 90-96 °C to the cylinder lining, cylinder heads, and first stage scavenge air cooler, while the low-temperature cooling circuit provides lower temperatures below 65 °C to second stage scavenge air cooler, and lubricating oil. Therefore, the type of engine affects the cooling circuits, and the amount of waste heat generated.

The potential of the WHR system to generate power depends on the installed engines onboard ships in terms of their size, rated power, number, efficiency, and their function onboard. Moreover, there is further information that must be gathered to design the WHR system such as the number of reefer containers, the need for power take-in (PTI) and/or power take-off (PTO), intentions concerning the use of the recovered WHRS energy, the use of PTO and PTI at the different running modes, service steam amount at sea (tropical, ISO and Winter conditions), etc. For example, the selection of applicable WHR system from turbocombunding technology depends on the engine size as STG is preferred to be installed onboard ships that use a main engine size <25,000 kW, while PTG is preferred for lower main engine size (< 15,000 kW) and the combined ST-PT is recommended to be installed onboard ship has main engine power > 25,000 kW [24].

3.7 Market availability of WHR technology

The practical limitations of WHR technologies in terms of market availability for maritime applications and in general for other industries are discussed. In general, the principal manufacturers of commercial ORC power plants are Atlas Copco, Ormat, GE Energy, Turboden, and Tri-O-Gen [29], [30]. Some ORCs built for maritime applications can currently be found on the market such as Alfa Laval which offers the 'E-Power Pack' [31]. E-power pack is considered a modular, stackable ORC unit with rated electrical power output of 100 kW_e to 200 kW_e, this product can generate electrical power from jacket water supplied at 75-109 °C, from saturated steam/thermal oil supplied at 120°C - 180°C and, and from exhaust gas supplied at temperature up to 550 °C. The E-power pack with a rated electrical output of 200 kW has a volumetric and gravimetric power density equal to 24.4 kW/m^3 and 0.042 kW/kg, respectively.

Orcan-Energy offers a similar product, called 'Efficiency Pack' [32], it can generate electrical power from a wide variety of liquid or gas heat sources onboard. These range from jacket water (supplied at 75–109°C) to engine exhaust gas (supplied at temperatures up to 600°C). Available in two sizes, the Efficiency pack can deliver a net electrical output of up to 100 kW or 200 kW per module, producing

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maximum results by adapting to the heat source with excellent partial load capacity. The Orcan's Efficiency pack is marine-certified by leading classification societies and operated/tested onboard catamarans of the Dutch shipping company Doeksen called "MS Willem Barentsz" and "MS Willem de Vlamingh" as shown in Figure 17. In Table 3.4, there are two different modules from Orcan Energy with rated power output equal to 100 and 200 kW that have a volumetric power density equal to 30.5 and 26.7 kW/m^3, while the gravimetric power density equals 0.0412 and 0.0408 kW/kg.

Figure 17 Orcan-Energy 'Efficiency Pack' installed inside the engine room of "MS Willem Barentsz"

Opcon Energy technology has developed an ORC system to be installed onboard ships called "Opcon Powerbox ORC" that can utilize low-grade waste heat, such as jacket cooling, scavenger air, and combustion gas cooling, and convert it into cost-effective power generation. In 2012, Opcon succeed to implement the first reference installation of Powerbox ORC onboard the Large Car-Truck Carrier "*MV Figaro"* and in this installation, it can supply at most up to 500 kW. The company has received official approval from Lloyd's Register for the use of its product at sea. Opcon Powerbox is available in several sizes and configurations both for hot water and wet steam and has a nominal generation capacity between 100-1600 kW. Opcon Powerbox ORC can reduce fuel consumption by between 5-10 percent, or increase existing power generation by a similar 5-10 percent without the need for larger engines or more fuel.

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Figure 18 Opcon Powerbox ORC Marine version installed inside the engine room of "MV Figaro"

There is another ORC system developed by Mitsubishi Heavy Industries in conjunction with Caltenix Technologies called "Hydrocurrent™ ORC 125EJW" [33]. It is designed to capture the heat from marine engine jacket water and convert it to electricity for shipboard consumption. The system can recover heat with temperatures as low as 80 °C to produce up to 125 kW of clean power and still leave enough heat in the jacket water for the freshwater maker. The system configuration is shown in Figure 19.

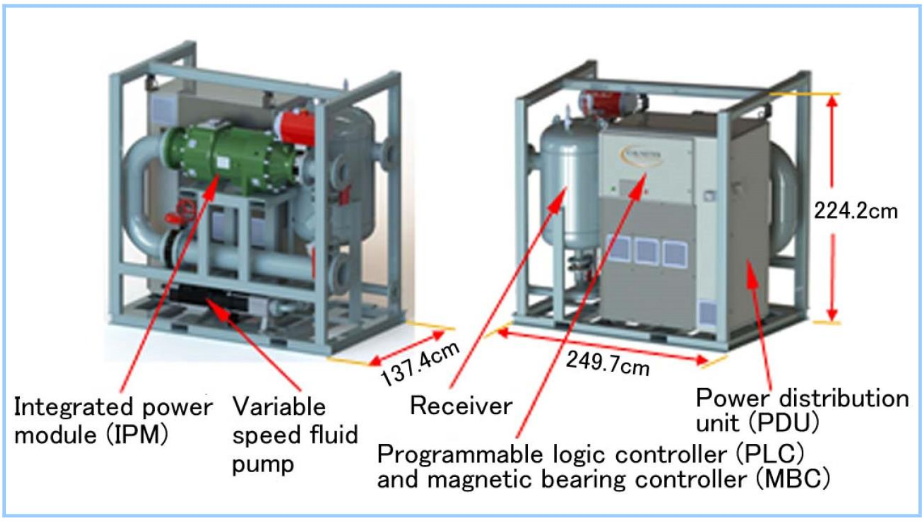

Figure 19 Hydrocurrent™ ORC 125EJW system components and their configuration

Climeon developed a marine WHR system based on ORC called "HeatPower 300 Marine". This product uses low-temperature waste heat (80-90 °C) existing on jacket water cooling and converting it into

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clean, carbon-free electricity. HeatPower 300 Marine has the ability to produce electric power up to of 355kW from a single unit. It is created for larger vessels with engine sizes from 15MW and up [34].

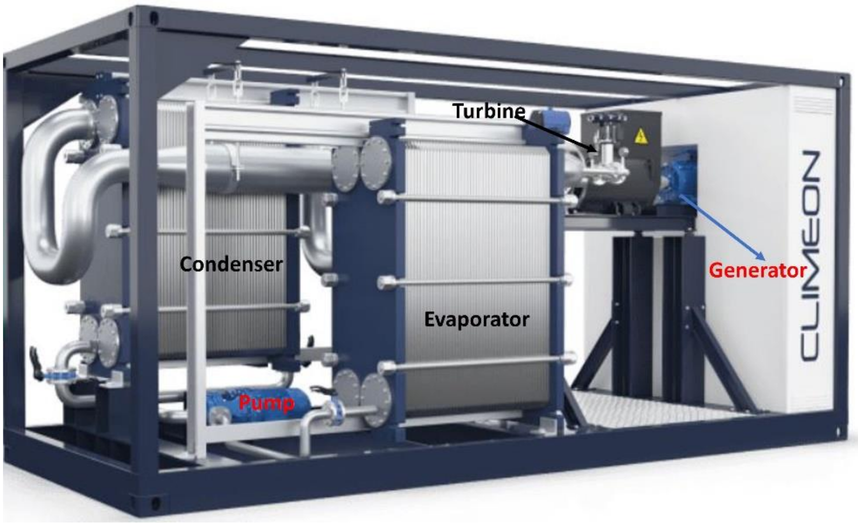

Figure 20 HeatPower 300 Marine system components and its configuration [34].

Other commercial ORC products could be adjusted for maritime applications. Enogia offers several ORC products, it can generate electrical power from water or exhaust gas heat sources with heat flow with temperatures between 70°C and 120°C, while their nominal output power ranges from 10 kW_e to 180 kW_e. The ENO-180LT is the highest module in terms of power capacity that can recover up to 2400 kWh and has a nominal power output of 180 kW, its volumetric and gravimetric density is 15.1 kW/m^3 and 0.024 kW/kg, respectively [35].

Furthermore, Enerbasque developed a thermal machine called “HRU-25” [36]to convert waste heat on the water at temperatures 85-95 °C into a maximum net electrical power equal to 21.5 kW with a 7.8% as net efficiency. The module has a lower volumetric and gravimetric power density equals 1.64 kW/m^3 and 0.0102 kW/kg, respectively. Moreover, Rank has developed ORC modules called the “MT category” [37] which uses heat sources with temperatures from 120 °C to 150 °C. and exploits thermal power from 150 kW to 1800 kW. The MT category has four different products (MT1-4) that generate clean electrical power ranging from 20 kW to 180 kW.

Adsorption cooling and desalination is a novel developmental technology, therefore there is a lack in the market of available products. For primary evaluation, the products of adsorption chillers are summarized in Table 3.4. The first product is from InvenSor [38] with a cooling capacity between 10 and 35 kW, the volumetric and gravimetric power density of the product is 15.2 kW/m^3 and 0.0292 kW/kg,

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respectively. The second adsorption chiller product is from SorTech [39] which is ideal for use in combination with CHPs, industrial waste heat, solar thermal plants, and district heating but can be adjusted for maritime applications. The SorTech eCoo 2 can generate cooling power up to 16 kW with a heating capacity equal to 50 kW and a maximum COP is 0.65. The package has dimensions of 800 mm (W) × 620 mm(D) × 1732 mm (H) with a floor space required equal to 0.5 m^2, while the operational weight with pump group and casing is 357 kg. This model can be integrated to deliver refrigeration power up to 128 kW. Also, Sortech offers another adsorption chiller called “eZea” that delivers refrigeration power up to 13 kW with a heating capacity of up to 40 kW and the maximum COP equals 0.53.

Thermal energy storage is considered a technological enabler used to better connect in time and space the highly intermittent available waste heat from the engine with the energy demands on board ships. Many commercial TES devices can be found on the market for applying it on maritime applications. Energy Nest developed a contenarilized STES system called “ThermalBattery“ [40] that operates with thermal oil or water/steam at temperatures up to 400°C. The dimensions (LxWxH) of the pack are 2.4 x 2.4 x 6.0 m, while the lifetime is estimated to be 30-50 years. Moreover, Eco-Tech Ceram has developed Eco-Stock [41], with operating temperatures ranging from 300°C to 1200°C to manage the intermittency and variability of deposits and energy consumption. The Eco-Stock is able to capture, store and return carbon-free Mega Watts that are less expensive than those resulting from the combustion of fossil materials (natural gas, oil, etc.) by controlling the duration, power, temperature, and flow rate of the energy flow. The maximum stored energy is 2.5 MWh with a discharge power equal 3 MW. The expected annual saving can reach 50,000 € with CO_2 reductions up to 1000 tons per year.

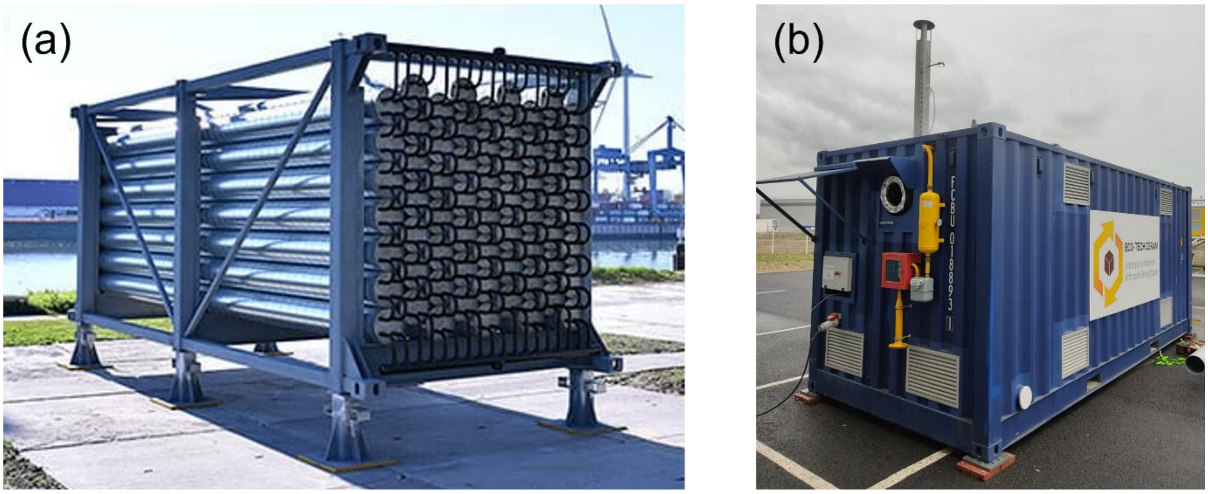

Figure 21 (a) Thermal Battery by Energy Nest [40] , (b) Eco Stock by EcoTech Ceram [41]

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Very few commercially Kalina cycles are currently commercially available. Most works on this type of cycle can be found in scientific literature using thermodynamic models and laboratory prototypes. Regarding the thermoelectric generators, they are available from various manufacturers including Tegmart, Hi-Z, Tecteg, and Marlow Industries [42]. All of the analysed TEG modules cost between 10 € and 70 €, for absolute power outputs in the range 1 W_e to 80 W_e.

Table 3.4: Market products of WHR technologies

WHR technology	Market products	Capacity (kW)	Volume (m^3)	Weight	Volumetric power density (kW/m^3)	Gravimetric power density (kW/kg)
ORC	Alfa Laval	100	3.12	2430	32.0	0.041
		200	8.2110	4800	24.4	0.042
	Orcan-Energy	100	3.27	2430	30.5	0.0412
		200	7.48	4900	26.7	0.0408
	Opcon	800	89.25	30000	8.96	0.0267
	Caltenix Technologies	125	11.96	3738	15.8	0.0334
	Enogia	180	11.96	7500	15.05	0.024
	Enerbasque	21.5	13.12	2100	1.64	0.0102
	Rank	20	11.42	5500	1.75	0.0036
		45	23.862	6500	1.89	0.0069
		100	32.625	8000	3.07	0.0125
		180	33.75	11000	5.33	0.0164
Adsorption chillers	InvenSor	10-35	2.30	1200	15.20	0.0292
	SorTech eCoo 2	16	0.859	357	18.62	0.0448
	SorTech eZea	13	0.620	234.5	20.97	0.0554
TES	Energy Nest	1500	34.56	-	43.4	-
	EcoTech Ceram	2500	-	-	-	-

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4 Applicability of boundary conditions to zhenit technology scenarios

This section aims at presenting a survey for the ZHENIT solutions and the different technology scenarios discussed in section 2 to be applied onboard different ship types. The ZHENIT solutions will be assessed based on the discussed boundary conditions in section 3 regarding the following key criteria: saving potential, technology maturity, and compatibility.

The saving potential is referred to the benefit that can be gained from applying WHR technology onboard the ship. The saving potential can be appeared in the lower fuel consumption, reduction of ship emissions, improvement of energy system efficiency and recoverable electrical power. The recoverable electrical power can be described as a percentage of the main engine's power, for example, a main engine power has a rated power equal to 1 MW and the WHR system achieved recoverable electrical power equal to 100 kW so the saving potential in this case can be 10% of the rated power. This recoverable power can be used to power auxiliary systems or hotel services and reduce the fuel consumption that covered this rated power. This measure can be assessed to be low or medium or high based on the expected potential of the WHR technology. The low metric is considered the minimum saving potential that can be gained from the WHR technology, the maximum metric is considered the maximum saving potential, and the medium is the average between the minimum and maximum saving potential.

The technology maturity refers to the current state of development of WHR solutions to be applied on board ships or other applications. This procedure can be divided into commercial, available for marine applications, available for other industries, or under research and development (R&D). Moreover, the commercial availability of technology can be categorized as an early stage or mature practice as the early stage refers to the availability of this technology on the market but with a small history of installations onboard ships, while the mature practice refers to the technology that has several products on the market and has a large history of installations onboard ships. The technology stage measure has a solid relationship with the implementation risk of this technology as the risk can be high if this technology is characterized to be in an early implementation stage or just a prototype, while the risk can be medium if the technology is in an early stage from a commercial availability point of view. However, the risk can be low if the technology is in mature practice as it is strengthened by the available information of its implementation onboard ships. For ease of assessment, this measure rating will be

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divided into 1,2, and 3 as 1 referred to the R&D stage or prototype, 2 referred to the early commercial stage, and 3 referred to the mature practice commercial stage.

The application of WHR for the maritime sector is based on its compatibility to be fitted inside the ship. Therefore, it is crucial to define the suitable ship type that can implement the ZHENIT solution over other ship types. For ease of compatibility definition, the ship types are categorized into different groups based on the considerations and boundary conditions that affect the applicability of WHR technology to be installed as discussed in section 3.

For example, the installation aspects as boundary conditions for WHR technologies can affect the selection of ship type that has a suitable compatibility level, whether the space of the installation is available onboard the ship type or not. The added weight of WHR technology may affect the stability of the ship like what can be occurred in the tug or small passenger ships or affect the maneuverability of the offshore supply vessels. The duty cycle is a key factor in defining the category of ship and influence the definition of WHR compatilbity. The duty cycle category is divided into continuous and intermittent, the continuous is referred to ships with long transit times that permit the WHR technology to reach its steady state operation. While intermittent duty cycle refers to ships with variable load profiles like what occurs in supply vessels or port tugs that prevent the WHR technology from reaching a steady state of operation. Finally, the power plant size onboard ships are considered one of the parameters that affect the categorization of ships. The different ship types are categorized into different groups as shown in Table.

Table 4.1: The compatibility matrix of ship types

Ship category	Ship type examples	Weight tolerance	Power plant size	Duty cycle	Ship power group
A – Ocean-going cargo ships	Container	Large	> 10 MW	Continuous	1
	General cargo	Large	> 10 MW	Continuous	1
	Dry bulk	Large	> 10 MW	Continuous	1
	Crude oil tanker	Large	> 10 MW	Continuous	1
	RO-RO ships	Large	> 10 MW	Continuous	1
	Chemical tankers	Large	> 10 MW	Continuous	1
	Gas carriers	Large	> 10 MW	Continuous	1

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Ship category	Ship type examples	Weight tolerance	Power plant size	Duty cycle	Ship power group
B- Passengers	Ferry/Cruise (Long)	Large	> 10 MW	Continuous	1
	Ferry/cruise (short)	Small	1 MW to 10 MW	Intermittent	2
	Crew boat	Small	< 1 MW	Intermittent	3
C- Fishing	Ocean-going	Small	1 MW to 10 MW	Continuous	4
	Shore	Small	< 1 MW	Intermittent	3
D- Services work	Offshore supply vessels	Large	1 MW to 10 MW	Intermittent	5
	Port tugs	Small	1 MW to 10 MW	Intermittent	2
	Fire fighting vessels	Small	1 MW to 10 MW	Intermittent	2
	Anchor handling tug supply	Large	1 MW to 10 MW	Intermittent	5
	Ice breaker	Large	>10 MW	Intermittent	6
	Cable layer	Large	>10 MW	Intermittent	6
	Drill ships	Large	>10 MW	Intermittent	6
E- Other ships	Heavy lift	Large	> 10 MW	Continuous	1
	Lake freighter	Large	> 10 MW	Continuous	1
	Inland ships	Small	1 MW to 10 MW	Intermittent	2

The above-discussed key criterias are applied and assessed to the different waste heat recovery technologies that have been mentioned in deliverable 1.1 as shown in Table 4.2: the four technologies investigated in the context of the ZHENIT project, and six other meaningful waste heat recovery technologies. Moreover, the categorization of each WHR system to its suitable technology scenario is mentioned in Table 4.2.

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Table 4.2: Summary of application of key criteria on ZHENIT solutions

Technology	Technology scenario	Saving potential		Technology Maturity	Compatibility (Ship category: power group)	Retrofittable
ORC	WH-to-power	Low: 5% Medium: 10% High: 15%		2 - early commercial stage	A: All B:All C:4 D:All E: All	Yes
Adsorption Desalination & Cooling	WH-to-Cooling WH-to-Freshwater	Low: 1% Medium: 3% High: 5%		1- R&D stage or prototype	A: All B:All C:All D:All E: All	Yes
Thermal Energy storage	WH-to-Storage	High: 25%		2 - early commercial stage	A: All B:All	Yes
Isobaric Expansion Engines	WH-to-power WH-to-cooling WH-to-Freshwater	Mean= 6.5 %		1- R&D stage or prototype	B: 2,3 C:All D:2 E: 2	Yes
Turbocompounding	WH-to-power	PTG	Low: 3% Mean: 4% High: 5%	2 - early commercial stage	A: All B:1 D:6 E: 1	Yes
		STG	Low: 4% Mean: 6% High: 8%	3- Mature practice		No

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Technology	Technology scenario	Saving potential		Technology Maturity	Compatibility (Ship category: power group)	Retrofittable
		ST-PT	Low: 8% Mean: 10% High: 11%	2 - early commercial stage		No
Steam Rankine cycles	WH-to-power	Low: 4% Mean: 8% High: 12%		3- Mature practice	A: All B:1 D:6 E: 1	Yes
Thermoelectric Generation	WH-to-power	Low: 1% Mean: 2.5% High: 5%		2 - early commercial stage	A: All B:All C:4 D:All E: All	Yes
Absorption Refrigeration	WH-to-Cooling	Low: 1% Medium: 3% High: 5%		2 - early commercial stage	A: All B:All C:All D:All E: All	Yes
Organic Flash Cycles	WH-to-power	Low: 5% Mean: 12% High: 19%		2 - early commercial stage	A: All B:All C:4 D:All E: All	No
Kalina Cycles	WH-to-power	Low: 6% Mean: 9% High: 11%		2 - early commercial stage	A: All B:All C:4 D:All E: All	Yes

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5 Conclusions

This report presented six technology scenarios for energy and cost-efficient Zero WH onboard ships based on the technologies investigated in the context of the ZHENIT project. These technology scenarios are WH-to-power, WH-to-storage, WH-to-upgrade, WH direct end-use, WH-to-cooling, and WH-to-fresh water. WH- to- power is the heat-capturing process that excess from the combustion process of marine engines to generate power. ZHENIT solutions that can produce power from waste heat include ORC, IEE, turbocompounding (PTG, STG and combined PT-ST), Steam Rankine cycles, thermoelectric generator, organic flash cycles, and Kalina cycles. The waste heat onboard ships can be captured, transported and stored to be used later for several purposes. This technology scenario helps to increase the sustainability of energy use and reduce operational costs. This scenaio can be accomplished by using Thermal energy storage (TES) that is designed to resolve the mismatch between the availability of thermal energy at a certain heat source, and the heat demand elsewhere by storing the heat for later use.

WH- to- upgrade scenario aims to to generate added value on the excess thermal energy for some on board demand such as steam or desalinated water. WH- to- cooling is a technology scenario aims at recovering waste heat onboard ships to cooling capacity that is required independent of the vessel type. ZHENIT solutions that can produce cooling capacity from waste heat include Adorption Desalination & Cooling and Absorption Refrigeration. There are some thermal end uses onboard ships that can benefit from the installation of WHR systems as the heat can be used for heating fuel, domestic hot water, space heating, cargo heating, cooling, and refrigeration.

There is a possibility to integrate WH valorization integrated interventions to enhance the performance of WHR. There is an example of this integration is defined in the combination of the technology scenario of WH- to upgrade with WH-to Freshwater technology scenario. Multi-effect distillation (MED) as a WH-to- upgrade solution can be integrated with Adsorption Heat Transformer (AHT) as a WH-to Freshwater technology to upgrade the waste heat from low heat grade to higher one through the adsorption process and improve the performance of desalination. The integration of Thermal Energy storage as a WH-to-storage technology with another technology from WH-to power such as ORC can be considered a solution to improve the WHR performance and overcome the problem of power fluctuations. Furthermore, this integration will permit the storing of waste heat excessed during sailing operations to be employed in port to cover the heating demand instead of using boilers and reduce fuel consumption.

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Also, there is a possibilty to integrate solution of WH- to power scenario with each other to improve the energy efficiency and extract more output electrical power. This can be done by integrating ORC and Kalina cycle in a combined WHR system by using the available heat sources onboard ships such as the exhaust gas, jacket cooling water and lubricants. Furthermore, the ORC can be integrated with a Steam Rankine cycle (SRC) and power turbine (PT) to generate more power by using the waste heat available in marine low-speed diesel engines.

Moreover, this report presented the market and boundary conditions that are relevant for the implementation of the different technology scenarios. These boundary conditions can be based on WHR technology itself, ship type, or the availability of market products. The boundary conditions based on the WHR system includes cost-effectiveness of WHR system, installation aspects, and system control. While the boundary conditions based on the ship itself can be the ship's operational profile, specifications of engines installed onboard the ship, and waste heat source characteristics.

This report provided an assessment of the ZHENIT solutions based on the discussed boundary conditions and technology scenarios using three main criteria which are saving potential, technology maturity, and compatibility. The compatibility measure of WHR system to be installed onboard ship is based on the different ship categories that are relevant to the discussed boundary conditions. The different ship types are categorized into different groups such as Ocean-going cargo ships, passenger ships, fishing ships, Services work ships, and other ships. Moreover, the ship category may have different ship power groups based on power plant size, duty cycle and weight tolerance.

According to the application of technology maturity measure to the ZHENIT solution, it is found that there are some solutions in the R&D stage or prototype such as Adsorption Desalination & Cooling and Isobaric Expansion Engines. While there are other solutions in the early commercial stage for maritime sector such as ORC, thermal energy storage, thermoelectric generation, Absorption Refrigeration, organic flash cycles, and Kalina cycles. However, there are solution on the mature practice commercial stage such as steam Rankine cycles and steam turbine generators.

Regarding the saving potential of the investigated solutions in the ZHENIT project, the saving potential can be in the range of 1-5% by using Adsorption Desalination & Cooling, thermoelectric generation, and Absorption Refrigeration. While the saving potential can be in the range of 5-15% by using ORC or in the range of 6-11% by using Kalina Cycles. The saving potential can be higher reaches to 25% by using thermal energy storage. By using turbo-compounding technologies, the saving potential is between 3% and 11%.

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