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

ZHENIT Solutions | SWOT analysis for replication

WP5 – Technologies evaluation and impact assessment towards replication

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

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2	Ethnicon Metsovion Polytechnion	NTUA	Greece	
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Abbreviation and Acronyms

Acronym	Description
AD	Adsorption Desalination
BRO	Batch Reverse Osmosis
CFC	Chlorofluorocarbon
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HTF	Heat Transfer Fluid
IEE	Isobaric Expansion Engine
LTES	Latent Thermal Energy Storage
MD	Membrane Distillation
MDM	Octamethylisodimethylsiloxane
MED	Multi-Effect Desalination
MM	Hexamethyldisiloxane
MSF	Multi-Stage Flashing
ODP	Ozone Depletion Potential
ORC	Organic Rankin Cycle
PCC	Pyridinium Chlorochromate
PCM	Phase Change Material
SRC	Steam Rankine Cycle
STES	Sensible Thermal Energy Storage
SWOT	Strengths Weaknesses Opportunities Threats
TCS	Thermochemical Energy Storage
TES	Thermal Energy Storage
TRL	Technology Readiness Level
WH-2-X	Waste Heat to X
WHR	Waste Heat Recovery
ZHENIT	Zero waste Heat vessel towards relevant Energy savings also thanks to IT technologies

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Executive Summary

The ZHENIT Project seeks to advance Waste Heat Recovery (WHR) as a crucial solution for attaining the 2030 targets set by the International Maritime Organisation and the European Union to decarbonize the shipping sector. The project's objectives include the development of new technologies, on-board validation, analysis of regulatory frameworks, and the creation of a replication roadmap at both regulatory and economic levels. Various solutions for waste heat recovery are explored, each with distinct temperature ranges, technology stages, saving potentials, and efficiencies. The primary technologies under scrutiny in the ZHENIT project encompass Organic Rankine Cycles (ORC), Thermal Energy Storage (TES), Sorption Desalination & Refrigeration and Isobaric Expansion Engines (IEE).

The present document constitutes the Deliverable D5.2 focused on "SWOT analysis for replication" and it is produced within Task 5.1, "How to replicate ZHENIT Solutions in different vessels (size, purpose etc.) towards at least 20% savings". This document aims at describing four of the technologies included in the project, i.e. Organic Rankine Cycles (ORC), Thermal Energy Storage (TES), Sorption Desalination & Refrigeration, Isobaric Expansion Engines (IEE), and analyzing them using the SWOT Analysis technique, which is a strategic planning tool used to identify and evaluate the Strengths, Weaknesses, Opportunities, and Threats involved in a project, business venture, or organization.

This report evaluates the main positive and negative aspects of the reference technologies, encompassing their potential for application in the context of ZHENIT objectives, taking into account the specific boundary conditions and the economic and environmental characteristics of each solution. The SWOT Analysis will support the replication for the WHR solutions presented, identifying the key features in terms of internal and external factors, becoming the reference tool for this specific task for evaluating the applicability of the technology in issue in the ZHENIT context.

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1 Introduction

This deliverable is named "ZHENIT Solutions SWOT analysis for replication" and it constitutes the D5.2 of the ZHENIT project, prepared in the framework of Work Package 5 and delivered at M21.

The aim of this task is to elaborate a SWOT Analysis for the WH-2-X solutions, namely Organic Rankine Cycles (ORC), Thermal Energy Storage (TES), Sorption Desalination & Refrigeration and Isobaric Expansion Engines (IEE), to better interpret their performance in the ZHENIT project context.

A SWOT analysis is a planning tool which seeks to identify the Strengths, Weaknesses, Opportunities and Threats involved in a project or organisation. It's a framework for matching a project's or organisation's goals, programmes and capacities to the environment in which it operates.

The SWOT analysis is commonly employed either at the initiation or as an integral component of the strategic planning process. This framework is esteemed for its influence in aiding decision-making, as it allows organizations to evaluate opportunities for success and proactively identify potential threats.

By conducting a SWOT analysis, businesses can pinpoint a market niche where they hold a competitive advantage. Individuals can also leverage this analysis to chart a career path that maximizes their strengths while staying vigilant to potential threats that may impede success. For optimal effectiveness, this analysis is best utilized when it pragmatically addresses and incorporates business issues and concerns.

As implied by its name, a SWOT analysis delves into four key elements:

- Strengths: Internal attributes and resources that contribute to a favorable outcome, such as a flexible product line or robust customer service;
- Weaknesses: Internal factors and resources that pose challenges to achieving success, such as a weak marketability or performance deficiencies;
- Opportunities: External factors that the subject can leverage or exploit, such as advantageous tax incentives or the adoption of innovative technologies;
- Threats: External factors that could endanger the entity's success, including intensifying competition or uncertainties in the supply chain.

In the ZHENIT framework, it is fundamental to clarify which are the objectives to be met in order to critically assess the Strengths, Weaknesses, Opportunities and Threats. Therefore, the project's goal is to find the most appropriate solution to achieve the net zero waste heat from vessel, purposing different waste heat recovery options. Consequently, the four categories previously described focus on the ability of the waste heat recovery technology to adapt to the goals of this project, observing not only the energetic scope, but the economic sphere too.

The present deliverable is structured as follows:

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- Chapter 1: Introduction;
- Chapter 2: SWOT Analysis of Organic Rankine Cycle;
- Chapter 3: SWOT Analysis of Thermal Energy Storage;
- Chapter 4: SWOT Analysis of Sorption Desalination & Refrigerant;
- Chapter 5: SWOT Analysis of Isobaric Expansion Engine;
- Chapter 6: Conclusions;

Starting from Chapter 2, each section contains a brief description of the technology involved in the analysis, and subsequently the SWOT Analysis itself, which explains in detail the most relevant aspects for the WHR technology in issue. Finally, a factsheet is presented, summarizing the key points highlighted in the relative paragraph. Figure 1-1 shows the model used for the factsheet.

This work is developed through the review of submitted ZHENIT deliverables. Particularly, the two main works studied are *D1.1 – WHR for Maritime applications catalogue*, and *D1.3 – Market scenarios and on-board boundary conditions for ZHENIT solutions*.

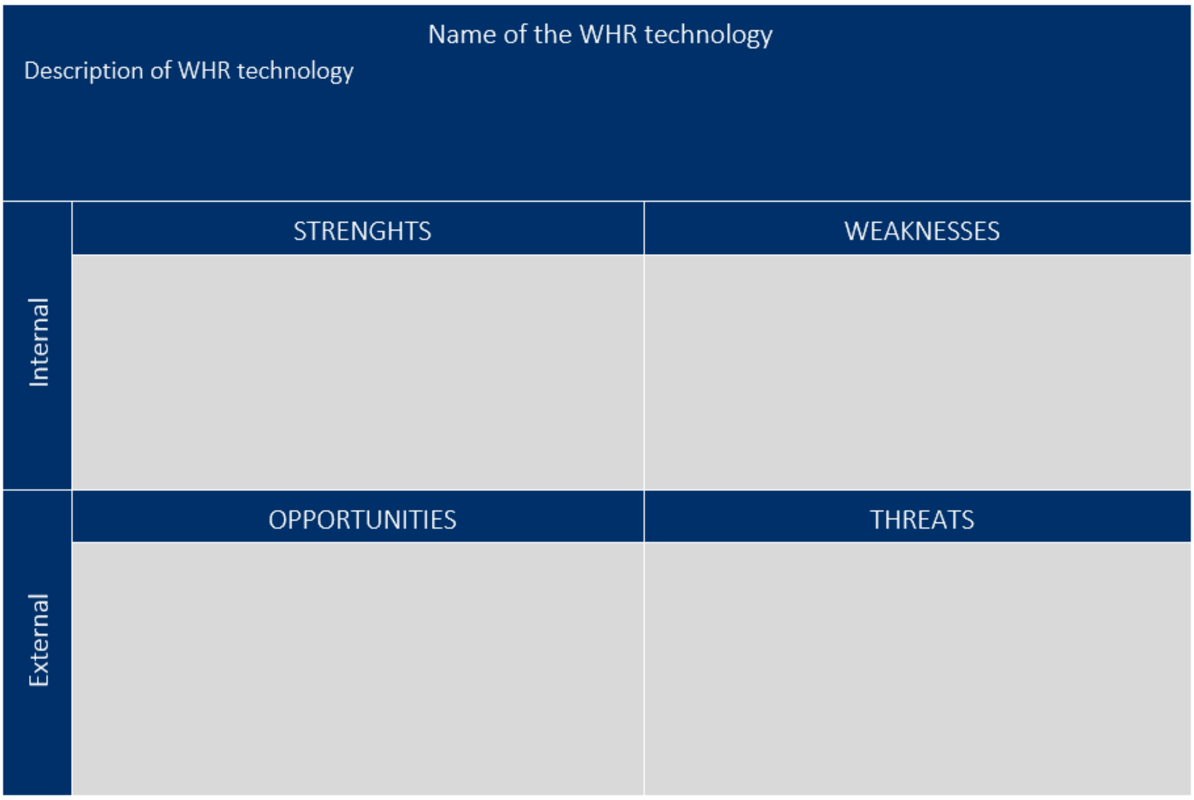

Figure 1-1: SWOT Analysis Factsheet Model

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2 SWOT Analysis of Organic Rankine Cycle

2.1 Technology presentation

The Rankine cycle is a thermodynamic cycle that converts thermal energy from a heat source into useful mechanical work through an expander/turbine train, generally to produce electricity. In its most basic configuration, a Rankine cycle is composed of an **evaporator**, an **expander (turbine)** connected to a **power generation unit**, a **condenser** and a **pump** in a closed fluid loop, as shown in Figure 2-1.

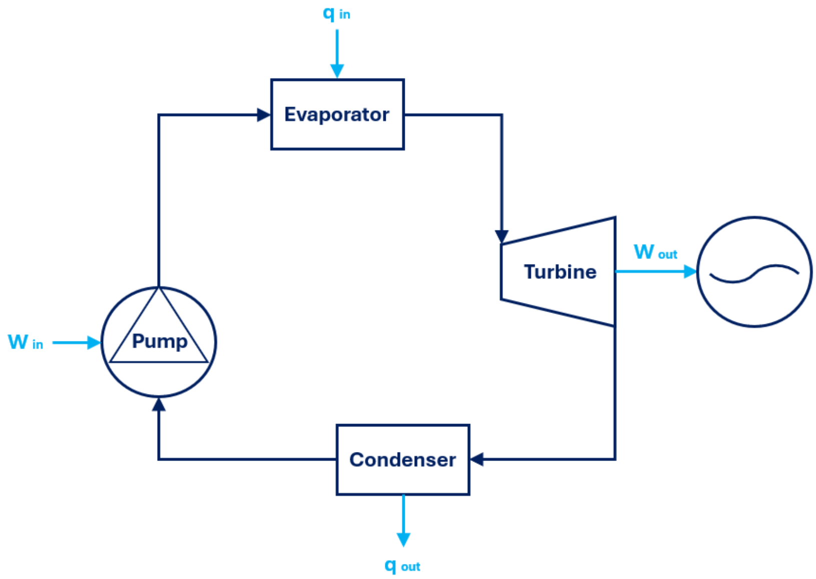

Figure 2-1: Schematic of Rankine Cycle for power generation.

The most traditional cycle consists of the so-called Steam Rankine Cycle (SRC), which uses water as working fluid. The Organic Rankine Cycle (ORC) uses a high enthalpy fluid, which works over a wider range of temperature, being particularly helpful with low temperatures. In ideal Rankine cycle, the fluid undergoes four fundamental thermodynamic processes:

- Adiabatic pumping
- Isobaric heating
- Isoentropic expansion
- Isobaric cooling

The performance of an ORC relates to the amount of useful work produced in relation to the thermal energy input to evaporate the working fluid and the electrical energy input to drive pumps and auxiliaries. Configuration and working fluid selection are two of the main factors which determine the

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performance of the ORC in the context of the application. Net power output of current commercial ORCs ranges from 10 kWe to 10 MWe. The net efficiency can vary between 5-25%, according to D1.3[1].

Regarding the system configuration, the gaseous fluid at the turbine outlet needs to be cooled down to low-pressure saturated liquid temperature, and the liquid fluid at the pump outlet requires heating to the high-pressure saturated vapour temperature. A common modification to the basic cycle is to recover the heat from the turbine outlet and transfer it to the fluid at the pump outlet via a heat exchanger (called recuperator or regenerator) to complete a recuperated or regenerated cycle. Turbine bleeding takes part of the hot working fluid to preheat the stream ahead of the evaporator, resulting in an overall increase to efficiency. The working fluid is divided into different pressure levels and processed in two different expanders. In dual loop or cascaded cycles, two ORCs operating with different working fluids leverage waste thermal energy from different temperature heat sources. This cycle is useful to combine multiple waste heat streams at different temperature levels, a likely scenario in marine energy systems.

The choice of the organic fluid depends on various factors, including the temperature range of the heat source, the target efficiency, environmental and safety considerations. Different organic fluids have different boiling points, critical temperature and thermodynamic properties, making them suitable for specific applications. The working fluids can be generally classified into three categories: wet, isoentropic and dry fluid. The distinction is better represented graphically by the T-s diagram in Figure 2-2.

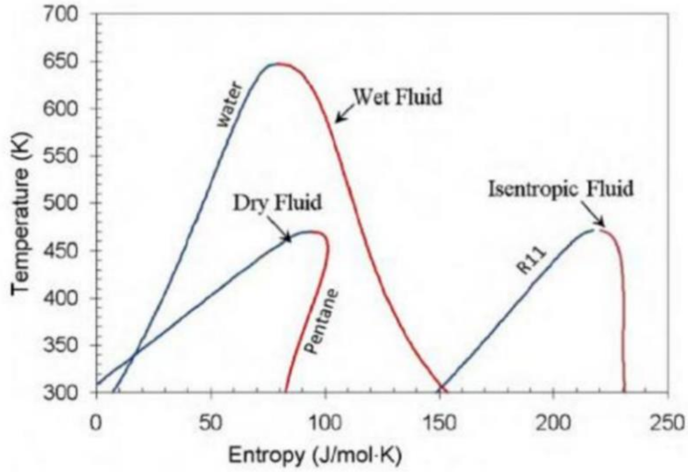

Figure 2-2: Classification of Rankine cycle fluids in T-s diagram (Source: Sharma[2])

[1] Giorgio Bonvicini, Samuele Da Ronch, Ahmed Elkafas, D1.3 – *Market scenarios and on-board boundary conditions for ZHENIT solutions*, ZHENIT, July 2023.

[2] Sarthak Sharma, *Analysis and Design of Organic Rankine Cycle based Power Plants*, Indian Institute of Science, 2019.

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Examples of common options are water (which is not suitable for ORC, as previously explained) as wet, R11 as isoentropic, pentane as dry fluid. The organic compound can be pure or a mixture. The working fluids for ORC are usually refrigerants such as CFC, HCFC, HFC, remembering that many of them are already phased-out or will be phased-down in short future, due to negative environmental implications. The selection of working fluid depends on the application field of ORC. In Waste Heat Recovery context, common examples are ethane, propane, butane, isobutane, pentane, ammonia, carbon dioxide, as studied by Haerving et al[3]. Analysis of the waste heat source on ships point towards heat sources in the temperature range 90 – 300 °C, in particular, the waste heat from engine exhaust gases at 190-300 °C, which constitutes 80% of the waste energy (generally after being cooled in a first stage inside the engine turbochargers), and a further 10% in jacket cooling fluids. The remaining 10% of waste energy could play strategic role on the ship for thermo-electrical purposes, although it constitutes a little amount for important energetic applications. ORCs with low boiling point working fluids have therefore good potential aboard large marine vessels.

Organic Rankine Cycle is considered a viable solution for power generation starting from the waste heat recovery on-board. The amount of input energy, and consequently the performance of ORC, depends on navigation conditions: during ship underway, machineries will release greater amount of heat, while during docking and stopping a lower amount of heat.

2.2 SWOT Analysis

STRENGHTS

The effectiveness of on-board systems using Steam Rankine Cycles is limited. This is mainly due to the temperature of available waste heat and the fact that water needs a high evaporation temperature to produce high-pressure steam (ideally above 350 °C). If the temperature is lower, the equipment needed becomes bulky, inefficient, and expensive. ORC are more efficient when utilizing lower-temperature waste heat on ships. Specifically, ORC uses organic fluids with lower boiling points than water, reducing the heat needed to get the desired pressurized vapors, and reducing the mechanical work and optimizing the net efficiency. By using organic fluids with lower boiling points, ORC guarantees higher flexibility.

As explained by Babatunde et al.[4], ORC performs better than the conventional steam Rankine cycle at the low operating temperatures due to five factors:

- favorable thermodynamic cycle modification/architecture;
- practical enthalpy drop and volume flow rate in the turbine;

[3] Jakob Haerving, Kim Sorensen, Thomas Joseph Condra, *Guidelines for optimal selection of working fluid for an organic Rankine cycle in relation to waste heat recovery*, Proceedings of the ICE – Energy, February 2016.

[4] A. Fakeye Babatunde and O. Oyedepo Sunday 2018 IOP Conf. Ser.: Mater. Sci. Eng. 413 012019.

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- favorable operating condition of the turbine;
- possibility of lower maximum operating pressure and consequently, reduced costs of associated components;
- the possibility of selecting positive gauge condensing pressure, hence, avoiding air infiltration.

The utilization of organic working fluids that can simply employ a single stage expander hence offering advantages of simple design, low capital and maintenance costs. Due to the comparatively lower specific enthalpy drop of organic vapors in turbines when compared to water vapor, it has become feasible to develop efficient ORC systems with modest capacities of few kW. These systems utilize single-stage turbo-expanders with reasonable tip speeds. In contrast, water vapor processes typically necessitate three or four-stage turbines, with the practical minimum size being limited to 2 MW in most cases.

WEAKNESSES

The optimal cycle performance and system architecture primarily depends on the selection of the best appropriate working fluid. There are conflicting stances imposed by some of the desired features of the organic fluid. For instance, high molecular weights and compressibility of working fluids enhance turbine efficiency and reduces the number of stages for axial turbines, but, however, high molecular weights fluids with high critical pressures require high rate of heat transfers and consequently, require bigger heat exchangers. Hence, there is need for trade-offs in optimizing the ORC systems configuration and architecture for the best overall performance of the system. Moreover, proper load calculation is also vital for choosing working fluids as it assists in accurate analysis. Organic fluids frequently experience chemical degradation and breakdown at elevated temperatures which regular water does not experience. The chemical constancy of the fluid consequently restricts the highest temperature. Furthermore, the fluid needs to be corrosion-resistant and suitable for engine components and lubricant oil. High Ozone Depletion Potential (ODP > 0.5) fluids such as R11, R113, R114, R115, and R12 should be avoided due to liquid formation during the turbine expansion phase in sub-critical ORCs. The same discussion is made for another environmental parameter: the Global Warming Potential (GWP). Many fluids have been phased out due to high levels of GWP, such as CFC and PCC. For what concerning to the safety, non-flammable, non-corrosive, and non-toxic properties are the most important features to satisfy. However, research is successfully developing sustainable alternatives, as properly explained in the “Opportunities” section.

ORCs are typically designed for biomass combined heat and power plants, waste heat recovery, low temperature geothermal sources, or solar applications. Recent developments are bringing this technology to explore maritime applications. The negative effects of marine conditions can be for sure the exposure to the salt, which may cause corrosion of the components, and the variable availability of waste heat compared to the above-mentioned use cases.

OPPORTUNITIES

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The research is pushing to find sustainable organic fluids which can guarantee high performance and low environmental impact. One idea is the use of green or sustainable working fluids, such as fluids generated from bio-materials. R2341a is an alternate refrigerant that is safer for the atmosphere than conventional ones since it has a minimal GWP and no ODP. Because of its elevated critical pressure and temperature, employing R134 in the Rankine cycle has been ascertained to make the cycle more efficient. As reported by Chowdhury and Ehsan[5], the high latent heat of vaporization observed for pentane, n-heptane and hexane suggests that these fuels may contribute to greater cycle efficiencies. Cyclopentane's favorable properties as a working fluid include a high critical temperature, low toxicity, and negligible contribution to global warming. Toluene is a feasible choice for high-pressure cycles due to its high vapor pressure. Working fluids with excellent thermal stability and low vapor pressure, such as hexamethyldisiloxane (MM) and octamethylisodimethylsiloxane (MDM), have been shown to increase Rankine cycle performance.

Another successful investigation in ORC application was performed by Ozdemir and Kilic[6], which analysed regenerative ORC for waste heat recovery applications using dry organic fluids such as R113, R114, R227ea, R245fa and R600a. Results showed that regenerative ORC has higher thermal efficiency compared with basic ORC, but it has produced less irreversibility rate, net power, and heat input values. R113 (boiling point close to 46 °C) has registered the highest thermal efficiency (between 19% and 24% with a turbine inlet pressure between 1,000 kPa and 3,500 kPa) and best exergy efficiency and irreversibility rate. These values are much more competitive than SRC, making ORC suitable for low temperature waste heat recovery. From such researches, it can be confirmed that higher efficiencies lead to lower energy costs, resulting in cost saving. Moreover, the compact structure of ORC can be seen as an opportunity to optimize space on ship, recovering energy through a smart relocation of auxiliaries on-board.

THREATS

When choosing working fluids, cost and availability are key aspects to consider. Conventional refrigerants, which are utilized in ORCs, are costly. This cost might be decreased by increasing the scale of manufacture of such refrigerants or by using minimal-cost hydrocarbons. Considering environmental concerns, hydrocarbons and other alternative working fluids are being investigated because they have lower global warming potentials, are more extensively available, and are less expensive. According to

[5] Abrar Sobhan Chowdhury, M. Monjurul Ehsan, *A Critical Overview of Working Fluids in Organic Rankine Supercritical Rankine, and Supercritical Brayton Cycles Under Various Heat Grade Sources*, International Journal of Thermofluids, Volume 20, 2023.

[6] E. Ozdemir, M. Kilic, *Thermodynamic Analysis of Basic and Regenerative Organic Rankine Cycles using Dry Fluids from Waste Heat Recovery*, Journal of Thermal Engineering, Vol. 4, No. 5, pp. 2381-2393, July 2018, Yildiz Technical University Press, Istanbul, Turkey.

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D1.3[7], the cost of ORCs can vary between 1,000-100,000 €/kW, while a common SRC ranges between 1,000-3,500 €/kW.

In Table 2-1 the SWOT Analysis factsheet summarizing the discussion about ORC is reported.

Table 2-1: SWOT Analysis of ORC

Organic Rankine Cycle		
ORC is a thermodynamic cycle that converts thermal energy from a heat source into useful mechanical work through an expander/turbine train. It exploits an organic fluid characterized by high enthalpy, which works at lower temperatures than Steam Rankine Cycle.		
Internal	STRENGHTS	WEAKNESSES
	• Ability to produce high-value energy carrier (electricity) for onboard uses • Flexibility and ease of management • Compact structure suitable for installation onboard • Relatively high efficiency	• Requires stable availability of waste heat (temperature/time) • Environmental impacts of the working fluid • Chemical degradation of working fluid • Maintenance challenge to maritime conditions
External	OPPORTUNITIES	THREATS
	• Efficient recovery of low temperature waste heat • Development of sustainable working fluids • Better space management and low infrastructural cost • Higher suitability for vessels with long routes and navigation periods	• High cost of working fluids • Lower suitability for vessels with discontinuous operation

[7] Giorgio Bonvicini, Samuele Da Ronch, Ahmed Elkafas, D1.3 – *Market scenarios and on-board boundary conditions for ZHENIT solutions*, ZHENIT, July 2023.

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3 SWOT Analysis of Thermal Energy Storage

3.1 Technology presentation

Thermal Energy Storage (TES) is a technology crafted to address the misalignment between the presence of thermal energy at a specific heat source and the heat requirements in another location. The temporal gap between the supply and demand for heat represents a significant contributor to inefficiencies at the system level. For instance, renewable thermal energy sources like solar or waste heat often exhibit intermittent patterns, and in the absence of storage, their capacity is restricted to immediate heat demands, resulting in the loss of any unutilized energy. TES can be classified into three categories:

- Sensible Thermal Energy Storage (STES);
- Latent Thermal Energy Storage (LTES);
- Thermochemical Energy Storage (TCS).

STES relies on increasing the temperature in the thermal mass of a material without any phase change, accounting only on the specific capacity of the selected material. It is the most developed TES technology, being characterized by simple and cheap design. Common materials used in STES include water, rocks, molten salts and ceramics. It is characterized by lower energy density compared to latent and thermochemical storage.

LTES leverages the phase change enthalpy during a phase transition of a so-called phase-change material (PCM). It is characterized by higher energy density capacity, accounting on both sensible and latent heat. LTES utilizes the consistent temperature thermal energy absorption inherent in the phase change of a storage medium, typically in a transition from solid to liquid or solid to solid. In the charging phase, a Heat Transfer Fluid (HTF) conveys heat to the PCM, causing it to melt, with the total chargeable energy determined by the phase-change enthalpy of the storage medium. Conversely, in the discharge phase, the HTF withdraws thermal energy from the PCM, leading to its solidification and return to its original state established during the charging process. Although it is a technology more complex than STES, LTES is considered a ready option to store large amount of energy density. Common PCMs include organic, inorganic and eutectic types compound and some of them are paraffin waxes, salt hydrates, fatty acids, metal alloys. Properties such as melting temperature, heat of fusion, thermal conductivity, material density can vary a lot in function of the selected PCM.

TCS is a heat storage technology that leverages reversible chemical reactions which are endothermic (i.e. absorb heat) in one direction and exothermic (i.e. release heat) in the other. Combining two separated compounds A and B results in the formation of product AB and release of enthalpy of reaction ΔH – the reaction in this direction constitutes the heat discharge step. Conversely, compound AB can absorb enthalpy of reaction ΔH which will cause A and B to separate, constituting the heat charge step. As long as the two products are kept separate, heat is stored indefinitely and without losses,

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assuming no material degradation by some other physical mechanism. This technology is less mature than the other previously described. The storage performance obtained would be high, with energy density about ten times higher than STES. Typical thermochemical materials involved are zeolites, silica gel, metal-organic compounds, salt hydrates.

3.2 SWOT Analysis

STRENGHTS

Aboard marine vessels, the time-profiles of available waste heat from the engine exhaust and of the on-board energy demand are very likely to be mismatched, and TES is an obvious solution to smooth out the fluctuations of the engine thermal losses. In this way, TES can be a key element to the synergistic implementation of multiple WHR technologies within an energy system. Consider a scenario where a cruise ship is sailing at maximum speed, leading to a surplus of waste heat generated from the onboard heat sources, exceeding the immediate requirements. Conversely, when the same cruise ship is docked in port, there arises a demand for power to facilitate hoteling services, including the operation of an electric boiler. An effective solution to address this situation involves the storage of excess waste heat generated during sailing for subsequent use in port. This approach aims to replace the utilization of the oil boiler or shore power, thereby reducing fuel consumption and mitigating emissions from the ship. 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.

The material selection depends on the temperature and, therefore, on the quantity of available heat, on the time of storage, on the final destination of the stored energy. Waste heat from ship, as already mentioned, ranges between 190-300 °C, and this should be one of the most relevant input data to start considerations about the TES typology's choice. There are both positive and negative aspects to remember in the utilization of a specific material, but this becomes an advantage since for every waste heat condition, a proper solution between STES, LTES and TCS exists, making TES a very flexible technology.

WEAKNESSES

The considerations about each solution comprehend both positive and negative aspects case by case.

Water-based STES is widely used in domestic applications for the delivery of hot water, and is a simple and cost-effective way of storing heat below 120 °C. The main weaknesses of STES are the relatively low energy storage densities below 100 kWh/m^3, the fluctuating power output during discharge, and heat losses, which limit storage duration and enforce good insulation.

The primary drawback of LTES is the inherently low thermal conductivity of PCMs, typically registering below 1 W/m/K. This necessitates the adoption of heat transfer enhancement methods, such as the creation of composite materials and the augmentation of heat transfer surfaces through the incorporation of nanoparticles. However, these approaches often result in a larger physical footprint,

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thereby diminishing the overall energy storage density of the system. In essence, there exists a tradeoff between enhancing charge/discharge power and reducing the energy storage density of the final LTES system.

Compared to the other two storage technologies, TCS shows the highest energy storage density, virtually lossless storage by keeping the constituting compounds separate with energy stored as chemical bonds in the so-called thermochemical material. A wide variety of reversible exothermic/endothermic reactions can be used as a TCS mechanism, and selection should be carried out according to the target application. 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 scale, and some system complexity associated with having to transport both heat and mass in/out of the TCS device. Energy storage density, and charge and discharge temperature strongly depend on selection of the thermochemical reaction.

The selection of the correct TES involves also discussion about the infrastructure. Indeed, a rule to consider is that the larger the volume, the larger the storage capacity. Large storage tanks, even for water, need relevant space, which is not easy to be found on ships. The TES should ideally be located close to the WH source to avoid too long pipelines. Moreover, the weight of the architecture is an aspect to control, implying a correct design of the storage positioning on the vessel.

Another weakness could be the energy surplus management. Typically, the energy in excess of storage media is used for adjusting the balance supply-demand or it is sold. Selling energy is fundamental not only from an economical point of view, but from an energetic one too. The time of storage influences the efficiency of the energy, and different TES technologies have different storage periods to avoid energetic losses. The higher the storage period, the larger the losses. While sailing, the ship is not connected to energetic network, making the sale of energy very complex.

OPPORTUNITIES

In order to better evaluate the positive and negative aspects of TES, a techno-economic assessment has been studied[8]. The analysis has been conducted over sensible and latent heat storage, since these two categories have the highest Technology Readiness Levels (TRL). Among STES materials, a focus on water is conducted: water acts as storage medium and heat transfer fluid; it is important to achieve stratification to maximize the efficiency of the storage; it is fundamental the use of pressurized tank to avoid water evaporation above 100°C; it is scalable without significant constraints; the efficiency reaches around 90%. Among PCMs, the ones with better properties for the cases studied were paraffin C-34 and $Ba(OH)_2 8H_2O$ (barium hydroxide octahydrate). For temperatures slightly above 100 °C, the paraffin has good volumetric thermal capacity but low thermal conductivity, however it is available on market and non-toxic. The salt hydrate has much higher volumetric thermal capacity and higher thermal

[8] Alberto Rossi Espagnet, *Techno-Economic Assessment of Thermal Energy Storage integration into Low Temperature District Heating Networks*, KTH School of Industrial Engineering and Management, 2016.

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conductivity, but it is toxic and poorly available on market. The costs analysis has revealed a large difference between the considered technologies: water tank solution costs between 3-11 €/kWh (depending on the tank volume), paraffin C-34 costs 31.59 €/kWh, and salt hydrates more than the others.

Regarding the policy framework, TES aligns with the increasing emphasis on environmental regulations and sustainability in the maritime industry, offering an opportunity for compliance and positive reputation among stakeholders.

THREATS

As previously explained, TCS is the least applicable technology due to poor mature technology. This is a threat since it would perform better than STES and LTES, but nowadays it is not convenient to invest on it.

In general, paraffin waxes and inorganic salt hydrates are considered the most commonly materials used for low-medium temperatures (around 100 °C), while salts and eutectics mixtures are the most proper choice in case of high temperatures (over 200 °C), remembering, however, their challenging availability on market. The choice of the storage material is complex and dependent not only on the physical and chemical issues. For instance, a specific material could fit the storage much better than another one, having, in contrast, higher maintenance costs and less marketability. In the case of ZHENIT context, a suitable choice depends on the trade-off between costs and performance, evaluating the temperatures involved in the waste heat recovery line and ship constraints, such as environment exposure, sailing time, space needed, available budget, etc.

The considerations made above are schemed in Table 3-1.

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Table 3-1: SWOT Analysis of TES

<table>
<tr><th colspan="3">Thermal Energy Storage</th></tr>
<tr><td colspan="3">TES is a technology designed to resolve the mismatch between the availability of thermal energy at a certain heat source, and the heat demand. Aboard marine vessels, the time-profiles of available waste heat from the engine exhaust, and of the on-board energy demand are very likely to be mismatched, and TES is an obvious solution to smooth out the fluctuations of the engine thermal losses.</td></tr>
<tr><td rowspan="2">Internal</td><th>STRENGHTS</th><th>WEAKNESSES</th></tr>
<tr><td>• Improved energy management
• Support in matching heat supply and demand
• Enhanced overall efficiency
• Flexibility and ease of management</td><td>• Space and weight constraints
• Materials compatibility challenge
• Difficult management of energy surplus
• Not working as standalone technology (requires heat recovery systems)</td></tr>
<tr><td rowspan="2">External</td><th>OPPORTUNITIES</th><th>THREATS</th></tr>
<tr><td>• Regulatory Compliance
• Wide choice of TES technologies
• Higher suitability for vessels with discontinuous operation (e.g. cruise ships)</td><td>• High costs for PCM
• Weight and volume constraints (e.g. for piping)
• Some of the technologies (e.g. TCS) are not mature yet</td></tr>
</table>

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4 SWOT Analysis of Sorption Refrigeration & Desalination

4.1 Technology presentation

Sorption is a reversible thermochemical or thermophysical reaction, forming the basis for various technologies aimed at producing cold power, clean water, or a combination of both in hybrid systems, among other thermal applications. The fundamental principle of sorption involves a porous material's capacity to capture water vapor or another gas and crystallize it onto its surface. Sorption encompasses adsorption and absorption, which are two distinguished physic phenomena. Adsorption is the adhesion of particles from a gas or a liquid to a solid surface, creating a film of adsorbate on the adsorbent. Absorption consists in the dissolution or permeation of a fluid, which is the absorbate, by a liquid or a solid, which are the absorbents. In **sorption refrigeration**, the process capitalizes on the low evaporation temperature achieved at a low partial pressure of the refrigerant. This involves extracting heat from a heat transfer fluid to evaporate the refrigerant, ultimately lowering the temperature of the heat transfer fluid to achieve the desired cooling effect (typically ranging from -2°C to 5°C). The temperature of the resulting cold stream is contingent on the evaporation temperature at low partial pressure of the refrigerant. **Sorption desalination**, on the other hand, involves the sequential evaporation, adsorption, and desorption of seawater into and from a sorbent material, ultimately condensing it back into purified desalinated water. In such systems, seawater functions as the refrigerant, requiring thermal energy for the regeneration of the adsorbent material and the desorption of water for subsequent condensation. The synergy of sorption refrigeration and desalination integrates these two technologies into a single hybrid system. The minimum temperature achievable for the generated cold stream is constrained by the evaporation temperature of seawater at low partial pressure, thereby the cold stream is used to chill.

An adsorption refrigeration and desalination process comprises three fundamental components:

- an evaporator;
- an absorber/desorber bed;
- a condenser.

Initially, a low-pressure and low-temperature liquid sorbate is converted into vapor in the evaporator, extracting heat from the surroundings. This heat is provided by a chilled water flow, which undergoes cooling in the process. The vaporized refrigerant then flows into an adsorber bed where the sorption process occurs. In refrigeration systems, the choice of sorbate influences the temperature at which evaporation occurs, determining the type of cooling effect achieved in the sorption cycle. In adsorption systems involving desalination, water always serves as the refrigerant. The desorbed water is then removed from the sorbent material, a phase referred to as the desorber mode of operation. As adsorption and desorption cannot occur simultaneously, a continuous cooling generation requires two adsorbers to operate asynchronously, forming a two-bed system. The desorbed water, in vapor form, is

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directed to a condenser where it undergoes natural convection and is condensed into a two-phase liquid/vapor state using cooling water.

Desalination technologies, commonly employed for the purification of water, can be broadly classified into two categories based on the method of water-salt separation: membrane desalination and thermal desalination. Desalination processes include established systems utilized on ships, such as multi-effect desalination (MED) and multi-stage flashing (MSF). Another method, membrane distillation (MD), operates on a partial pressure differential across a hydrophobic membrane, enabling it to function with lower heat and pressure requirements compared to alternative desalination processes. MD utilizes low-grade waste heat, like the water used for an engine cooling system on board a ship, to produce freshwater by combining heat and mass transfer across the membrane. Waste heat evaporators represent an effective means of freshwater production on ships, leveraging sources such as flue gas, steam, and jacket water cooling. Distillation can be applied to seawater, brackish water, or contaminated feed water.

In summary, sorption refrigeration can be considered a WH-to-cooling instrument, while sorption desalination a WH-to-freshwater one. These two options can bring many advantages in the marine sector context.

4.2 SWOT Analysis

STRENGHTS

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. In refrigeration systems, the choice of sorbate affects the temperature at which evaporation occurs and therefore the type of cooling effect obtained from the sorption cycle. There are many adsorption refrigeration common working pairs as fluid such as activated carbon-methanol, activated carbon-ammonia, zeolite-water, silica gel-water, calcium chloride-ammonia. The thermal conductivity enhancement of the adsorbent is one effective way to improve the heat transfer in adsorption systems. Adding the materials with good thermal conductivity into the adsorbent is one of the most commonly used methods in the research on the heat transfer enhancement of the adsorbent. For example, the thermal conductivity of calcium chloride is only 0.1–0.2 W/(m °C), and it will increase by ten times after some graphite powder is added[9]. Water and ammonia are good candidates for refrigeration as evaporation can occur down to 0 °C and -60 °C respectively. In any adsorption system where desalination occurs too, water is always the refrigerant. Ammonia-water systems can provide very low

[9] D.C. Wang, Y.H. Li, D. L, Y.Z. Xia, J.P. Zhang, *A review on adsorption refrigeration technology and adsorption deterioration in physical adsorption systems,* Renewable and Sustainable Energy Reviews, 2009.

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refrigeration temperatures (down to -60 °C) compact unit size due to the low specific volume of NH_3 operating at high pressures, and trouble-free operation with no risk of crystallization. As specified by Aleyani et al.[10,] the cooling tower and associated pumping system capacities of this type of absorption refrigeration are twice the size of those of vapor compression refrigeration systems characterized by higher initial and operating costs.

Desalination methods for water purification include membrane and thermal processes. Membrane distillation uses low-grade waste heat, suitable for shipboard applications. Waste heat evaporators, leveraging sources like flue gas and steam, are effective for freshwater production on ships from seawater, brackish water, or contaminated feed water. The most energy-efficient desalination process is Heat Recovery Evaporator (HRE). The process uses waste heat, which is typically released into the atmosphere but that can be conveyed to other routes, 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. HRE provide benefits such as weight reduction, a compact footprint, and the absence of replacement parts. Consequently, they find application on various types of ships, including tankers, cargo vessels, offshore supply vessels, and military vessels like submarines, aircraft carriers, and destroyers.

One potential advantage of thermal desalination compared to membrane separation is its ability to make use of low-grade exhaust heat while maintaining a low top brine temperature. However, the efficiencies reached by these systems are far from the reverse osmosis, which is the most efficient existing desalination technology with an exergetic efficiency of about 32%.[11]

Silica gel, a porous form of silica dioxide, is a promising material for adsorption desalination, as it exhibits a high affinity for water vapor. In a closed environment, the pressure is lowered until boiling, and an energy source is introduced to establish equilibrium. Once saturated, silica gel is heated to a specific temperature, initiating desorption of the vapor, which is then collected and condensed into a clean product. Silica gel's effectiveness is attributed to its partially dehydrated polymeric structure and high

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[10] Sami M. Alelyani, Nicholas W. Fette, Ellen B. Stechel, Pinchas Doron, Patrick E. Phelan, *Techno-economic analysis of combined ammonia-water absorption refrigeration and desalination*, Energy Conversion and Management, 2017.

[11] Mistry KH, McGovern RK, Thiel GP, Summers EK, Zubair SM, Lienhard JH., *Entropy generation analysis of desalination technologies*. Entropy 2011; 13:1829–64.

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specific surface with numerous pores. As experimented by Mdletshe et al.[12], silica gel out performed zeolite, which is typically more expensive, when they were both tested in the same controlled parameters of pressure and temperature. However, rejecting or desorbing the adsorbed water vapour was a difficult path for both materials. It was observed that silica gel yield far better vapour recovery than zeolite even though there was not a case where 100% desorption that was observed in both adsorbent materials. The best adsorption capacity performance of the tests was 65 g of water vapour for 200 g of silica gel. While zeolite was capable of adsorbing water vapour worth 15% of its dry mass, silica gel was capable of adsorbing 32.5% of its dry mass at the same experimental conditions.

WEAKNESSES

Brine disposal and energy consumption are the two of the most important challenges for desalination. Adsorption Desalination (AD) consumes much more energy than membrane processes such as Batch Reverse Osmosis (BRO). In AD the separation of salt and water molecules occurs through the adsorption of water vapor onto a solid adsorbent material. This process requires energy to regenerate the adsorbent material, usually through heating. The energy consumption during the regeneration phase is a significant factor contributing to higher energy requirements in adsorption desalination. On the other hand, reverse osmosis relies on a different principle, where water is forced through a semi-permeable membrane to separate salts and impurities. While there is energy required to pressurize the water for the process, it is generally lower compared to the energy needed for the regeneration phase in adsorption desalination.

The choice of the materials involved in sorption processes is challenging due to trade-off considerations. Despite silica gel’s potential, there are challenges. Energy transfer is crucial due to silica gel's low thermal conductivity. The transition from adsorption to desorption requires substantial energy, impacting daily water production if not well-designed. Silica gel degradation, caused by factors like thermal stress and metal ion pollution, can diminish sorption ability, necessitating maintenance or replacement. While zeolite can be an alternative, it has lower adsorption capacity and desorbs at higher temperatures. Vacuum conditions pose additional challenges, affecting sorption characteristics and potentially leading to desorption at inappropriate times. Air leakage is a common issue, demanding high-quality vacuum systems and regular maintenance. Despite these barriers, adsorption desalination remains appealing due to its unique energy consumption pattern.[13]

OPPORTUNITIES

The brine treatment is quite challenging, but sorption technology can be considered an opportunity. The use of AD to treat brine downstream of conventional desalination can further increase the overall

[12] Z. Mdletshe, V. Msomi, O. Nemraoui, *Experimental investigation of the adsorbents using pressure and thermal swing for adsorption and desorption*, Results in Engineering, 2022.

[13] Jasper Schakel, *A critical review of Adsorption Desalination: The road to sustainable desalination or whisful thinking*, 2019.

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recovery in the desalination system and minimize the volume of brine for disposal. In addition, AD enables a multipurpose desalination system that can simultaneously produce freshwater, high-quality distilled water, and cooling power. Thus, hybridization with AD is an attractive solution, not only to address the environmental problem of brine disposal, but also to provide valuable products (distilled water and cooling) while capturing low-grade thermal energy. In other words, a hybrid BRO-AD system could be a competitive solution to address the critical issues of energy minimization and brine management.[14]

THREATS

The expense for initial investment and operation of conventional desalination technologies are quite high. The energy costs for unit water production by multi-stage flashing or reverse osmosis are higher than that of potable water produced from surface water and underground water resources. According to Shazad et al.[15], the typical amount of energy required for unit water production for different feed water quality is so represented: 0.37 kWh/m^3 from lake or river; 0.48 kWh/m^3 from groundwater; 0.62-0.87 kWh/m^3 from wastewater treatment; 1.0-2.5 kWh/m^3 from wastewater reuse; 2.6-8.5 kWh/m^3 from seawater.

In general, seawater treatment is not only highly energy intensive because of feed water quality but also impact environment in a number of ways such as energy utilized by desalination processes increase environmental pollution, concentrated and hot brine can effect marine life, contamination of water aquifers due to pretreatment chemicals. However, Sorption Refrigeration & Desalination process is less invasive in noise pollution and corrosion materials.

The table below provide the SWOT analysis considering the study conducted.

[14] Kiho Park, Ibrahim Albaik, Philip A. Davies, Raya Al-Dadah, Saad Mahmoud, Mohamed A. Ismail, Mohammed K. Almesfer, *Batch reverse osmosis (BRO)-adsorption desalination (AD) hybrid system for multipurpose desalination and minimal liquid discharge*, Desalination, 2022.

[15] Muhammad Wakil Shahzad, Muhammad Burhan, Li Ang, Kim Choon Ng, *Energy-water-environment nexus underpinning future desalination sustainability*, Desalination, 2017.

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Table 4-1: SWOT Analysis of Sorption Refrigeration and Desalination

	Sorption Refrigeration & Desalination	
	Sorption refrigeration is a type of refrigeration technology to produce cooling effects. The basic idea is to use a sorbent material that can absorb or adsorb a refrigerant, typically a volatile liquid, and then release it when needed to achieve cooling. Sorption desalination is a process that combines sorption principles with desalination techniques to produce fresh water from saline or seawater. It typically involves using a sorbent material to remove water vapor from the air or another gas stream and then condensing that vapor into clean water. This process is often driven by low-grade heat sources. The systems can be implemented in a hybrid technology.	
	STRENGHTS	WEAKNESSES
Internal	• Dual functionality to cover onboard needs (cooling and freshwater production) • Improved energy efficiency • No problems of corrosion and crystallization compared to vapor compression • Low maintenance required • High silica gel performance	• Higher energy consumption of adsorption desalination compared to reversed osmosis • Working fluid challenge • Requires integration with existing ship plants and related control systems
	OPPORTUNITIES	THREATS
External	• Space for system integration • Availability of hybrid solutions • Brine management • Best suitable for passenger ships, having high cooling and freshwater needs	• High investment for seawater treatment • Environmental impact on seawater • Ship adaptation constraints (e.g. for piping) • Less suitable for cargo ships with limited hotelling loads

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5 SWOT Analysis of Isobaric Expansion Engine

5.1 Technology presentation

Isobaric expansion engines are a type of heat engine that operates under constant pressure conditions during the expansion phase. Work is extracted from an isobaric gas expansion occurring within a cylinder. The most common example of an isobaric expansion process is the expansion stroke in a reciprocating piston engine when the piston moves down in the cylinder while the intake or exhaust valve is open, allowing for constant pressure conditions. Traditional IEEs are **Worthington** and **Bush** type engines, while nowadays the most common distinction is made between **direct-acting steam pumps** and **thermo-compressors**. They are engines with no polytropic expansion (e.g., Stirling or Ericson engines). The working principle of isobaric expansion engines is based on the continuous isobaric expansion and compression of a working fluid, which is supposed to have high thermal expansion at high temperature and low compressibility at low temperature. The IEEs are particularly attractive as **vapor-driven pumps** and **compressors** due to their lack of complex kinematics and multiple energy conversion steps. In such applications, heat can be efficiently used to provide direct pumping and compression, that is, without intermediate generation of shaft power or electricity, its transmission and then conversion back to mechanical energy typical of today's industry. The energy from the pumped liquid flows can be converted to shaft power (rotary motion) or electricity using off-the-shelf hydraulic motors. Another option is the so-called pump as turbine technology, which uses mass-market centrifugal pumps that operate in reverse mode i.e. as turbines. In this case, the installation is turned into a heat-to-power converter.

Direct acting pumps, also called “reciprocating pumps”, are machines characterized by a simple configuration. The reciprocating motion of the piston unit is accompanied by pumping and suction of a liquid in the pumping cylinder. The pump uses a very simple valves actuation system without a cut-off mechanism and has no crank gear and no flywheel. Depending on the diameters of the steam and pumping pistons, the discharge pressure of the liquid to be pumped can be equal to, lower or higher than the steam pressure. The pump can operate at very high temperatures (up to 400 °C), pump liquids in a very broad range of viscosities and compress gases. The most traditional configuration of this engine is the non-regenerative Worthington-type engine, but one possible modification consists in the realization of the regenerative Worthington-type engine, which is characterized by the presence of a regenerator. The main difference with thermo-compressors is the method used to increase the fluid pressure: direct acting pumps exploit mechanical work, while the thermo-compressors exploit the energy of a high pressure vapor that compresses a low vapor one.

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5.2 SWOT Analysis

STRENGHTS

IEEs permit to use heat for the compression and pumping directly, without the intermediate step of electricity generation, transmission and further conversion back to mechanical energy. IEE machines are attractive for electricity generation in low and medium power ranges, representing a valid solution for WH-to-Power. One of the main advantages of the isobaric expansion engine is the potential for work extraction from small temperature differences ($\Delta T \geq 30$ °C) and using low temperature heat sources (≥ 40 °C). In these temperature regions, the techno-economic performance of other waste heat to power converters, such as ORCs or other types of heat engines, is insufficient to justify their use. Another feature of isobaric expansion engines is their relatively simple design due to the isobaric or near-isobaric nature of the expansion process, enabling their use as simple compressors, pumps and other converters with specific speeds and torques. On board ships, one of the main waste heat sources available is the low-grade heat sources, which is considered hard to be recovered, leading to possible low efficiency. 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, optimizing the efficiency. Special heat pumps can be used to generate higher grade of heat approximately 100 °C from waste heat at 45 °C, connected properly with the engine in issue.

The Worthington-type IE machines can be integrated with all types of heat exchangers, including the most economical ones (gasketed and brazed plate, pillow plate etc.). Moreover, the large internal volume can even be useful for dampening pressure pulsations. In addition, this permits Worthington engines to use multiple heat sources and heat sinks with different temperatures. Direct acting pumps are considered more market ready than thermo-compressors since they are very simple, reliable and cheap.

WEAKNESSES

In spite of the attractiveness of the isobaric expansion machines, all attempts to develop a ready-to-market thermo-compressor have failed. It is commonly assumed that the thermo-compressor represents a particular type of the Stirling engine with typical disadvantages inherent in all Stirling engines. First of all, the thermo-compressor is very sensitive to the so-called dead volumes. Indeed, the heater, cooler, regenerator and all connection pipelines have internal volumes, which are detrimental to the efficiency and the power density. This harmful effect increases rapidly with the machine power. The second drawback is the low thermal expansion of gases. The power density of the machine is proportional to the difference between the maximum and the minimum cycle pressures. A high pressure difference can be obtained only at a very high temperature of the heat source and/or at a high initial pressure of the gaseous working fluid in the machine. The use of gases as working fluids at very high pressure makes the sealing very difficult. Even with low-output machines, the kinematic mechanism required to operate the dual pistons and the required high accuracy of single-piston Stirling

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engines make them very expensive. Both conditions require expensive heat resistant alloys and thick walls worsening heat exchange. One way to overcome these two problems is to use dense working fluid. However, the compatibility of the dense working fluid with the system is challenging. The fluids should have high thermal expansion per kilowatt heat supplied and low compressibility in the liquid phase. The dependence of enthalpy on the pressure and temperature that is favorable for efficient regeneration is the most important requirement toward the working fluid properties. Moreover the working fluid should be non-toxic, environmentally acceptable (taking care of indicators such as GWP and ODP), stable, and non-corrosive. According to Sleiti[16], ammonia and R32 have the highest efficiencies at high ΔP of 50 bar for the heat temperature range 100–300 °C, registering values only around 9%. R161 has high performance for ΔP higher than 10 bar up to 50 bar for the full range of heat temperature from 80 to 300 °C, which makes R161 the choice fluid for a wide range of applications. Theoretically, Bush-type engines are more efficient than Worthington ones; however, the high efficiency can only be realized if dead volume of the heat exchangers does not severely influence the engine power and efficiency, which is a condition difficult to be achieved.

Worthington-type engines show some weaknesses too. Since these pumps continue to deliver the same capacity, any attempt to throttle the discharge flow may overpressure the pump casing and/or discharge piping. Thus no reciprocating pump should ever be started or operated with the discharge block valve closed. Flow is regulated by speed. In rare cases that require a discharge throttle valve, an automatic bypass valve that is piped back to the suction source must be provided. Many reciprocating pump installations suffer from problems that can lead to excessive maintenance costs. Typical examples are noise and vibration in the piping and the pump. Vibration can lead to loss of performance and failure of valves, crossheads, crankshafts, piping, and even pump barrels.[17]

OPPORTUNITIES

According to D1.3, the price of this solution ranges between 500-2,500 €/kW, being easy economically feasible. The Worthington direct-acting steam pump and the Bush compressor have simpler design than Stirling or Ericson engines making them cheaper, too. In addition, the ability of these engines to operate using heat directly, which makes them even more attractive for pumping and compression applications, allow to create power without high operational costs.

Unforeseen operational challenges, such as variability in waste heat sources or changes in operating conditions, may pose threats to the consistent and reliable performance of isobaric expansion engines. A clever solution can be to connect Isobaric Expansion Engines to other technologies that allow stability

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[16] Ahmad K. Sleiti, *Isobaric Expansion Engines Powered by Low-Grade Heat—Working Fluid Performance and Selection Database for Power and Thermomechanical Refrigeration,* Energy Technology, 2020.

[17] Sander Roosjen, Maxim Glushenkov, Alexander Kronberg and Sascha Kersten, *Waste Heat Recovery Systems with Isobaric Expansion Technology Using Pure and Mixed Working Fluids*, July 2022.

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in waste heat temperature profile and efficient heat exchange. Challenges in integrating isobaric expansion engines with existing ship systems and infrastructure may hinder their adoption, particularly in retrofitting existing vessels.

THREATS

As already discussed, Isobaric Expansion Engines are difficult to be fit for high performances, since the efficiencies reachable are not so high. Operational scenarios may be complex in ship context if input conditions are variable. The compatibility with heat exchangers and other auxiliaries may be complex. Integrating new technologies with the ship's existing machinery and power generation systems requires careful engineering to ensure compatibility and efficiency. Thermo-compressors, which seem unready for clever application without high technological and operational costs, suffer problems of compatibility with heat exchangers. Moreover, the noise caused by the engines can affect the comfort on-board, impacting the social acceptance.

The analysis developed in this chapter is described in Table 5-1.

Table 5-1: SWOT Analysis of Isobaric Expansion Engines

Isobaric Expansion Engine		
Isobaric expansion engines are a type of heat engine that operates under constant pressure conditions during the expansion phase. Work is extracted from a theoretically isobaric gas expansion occurring within a cylinder. The energy from the pumped liquid flows can be converted to shaft power or electricity. Two main IEE configurations exist: Worthington-type and Bush-type engines.		
Internal	STRENGHTS	WEAKNESSES
	• Recovery of low-temperature heat sources • Simple design • Power generation without intermediate steps • Easy integration with heat exchangers	• Vibration and noise problems • Low efficiency • Dense working fluid and heat exchangers compatibility for thermo-compressors
External	OPPORTUNITIES	THREATS
	• Low cost for implementation • Retrofitting existing vessels infrastructure	• Low technology readiness for thermo-compressors • Complicated integration onboard due to waste heat conditions variability.

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6 Conclusions

This document, recognized as Deliverable D5.2, has constituted the "SWOT analysis for replication" for ZHENIT project, produced within Task 5.1, "How to replicate ZHENIT Solutions in different vessels (size, purpose etc.) towards at least 20% savings". The present work has described four of the technologies included in the project, specifically: Organic Rankine Cycles (ORC), Thermal Energy Storage (TES), Sorption Desalination & Refrigeration, Isobaric Expansion Engines (IEE). The scope of the study has been analyzing those technologies using the SWOT Analysis technique, which is a strategic planning tool used to identify and evaluate the Strengths, Weaknesses, Opportunities, and Threats involved in a project, business venture, or organization. This tool is developed to sustain businesses for finding competitive advantages. The SWOT analysis searches for internal and external positive and negative aspects of the specific solutions purposed, in the framework of waste heat recovery on ships.

Concerning the Organic Rankine Cycle, the system allows to save large amounts of heat, particularly from low temperature origin. ORC is designed for onboard power generation, offering flexibility, easy management, compact structure, all while maintaining good efficiencies. It employs sustainable working fluids, features a space-efficient design with low infrastructure costs, and is highly suitable for vessels with long routes and extended navigation periods. On the other count, negative aspects of ORC are the need for stable waste heat availability, the environmental impact and chemical degradation of working fluids, challenges in maintenance within maritime conditions, high costs associated with working fluids, and potentially lower suitability for vessels with discontinuous operation.

Regarding the Thermal Energy Storage, this technology comprehends three main storage typologies (Sensible Thermal Energy Storage, Latent Thermal Energy Storage, Thermochemical Energy Storage), each of which characterized by specific features. In general, the storage technology offers improved energy management, supports the matching of heat supply and demand, enhances overall efficiency, provides flexibility in management, ensures regulatory compliance and it is highly suitable for vessels with discontinuous operations, such as cruise ships. However, challenges associated with the system implementation include space and weight constraints, compatibility issues with materials, difficulty in managing energy surplus, dependency on additional heat recovery systems, high costs associated with Phase Change Materials, constraints in adapting the system to ships and the early-stage development and lack of maturity of certain technologies like TCS.

Sorption and Desalination System is another Waste-Heat Recovery methodology, associated with the ability to transform a fluid such as water into a benefit. It provides dual functionality for cooling and freshwater production, emphasizing improved energy efficiency, corrosion and crystallization avoidance, low maintenance requirements, high silica gel performance, efficient space integration, availability of hybrid solutions, effective brine management, and is best suited for passenger ships with high cooling and freshwater demands. It is relevant to consider also the higher energy consumption compared to reversed osmosis, challenges associated with the working fluid, the need for integration with existing ship plants and control systems, a high investment for seawater treatment, potential

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environmental impact on seawater, constraints in adapting the system to ships and its lesser suitability for cargo ships with limited hotel loads.

Isobaric Expansion Engine is a mature technology used for power generation, exploiting the mechanical work produced by the heat recovery. It is notable for efficiently recovering low-temperature heat sources, featuring a simple design, facilitating power generation without intermediate steps, enabling easy integration with heat exchangers, offering cost-effective implementation, and allowing for the retrofitting of existing vessel infrastructure. Negative aspects of these engines are potential challenges with vibration and noise, lower efficiency, compatibility issues for thermo-compressors regarding dense working fluids and heat exchangers, low technology readiness for thermo-compressors, and the complexity of onboard integration.

In conclusion, the four WHR technologies in issue have revealed favorable starting points for the implementation on marine vessels, being capable of generating benefits from the heat recycling, improving the efficiency and contributing for satisfying environmental constraints. Each technology can fit better than another depending on the objective. The spectrum of possible solutions is large, and it can cover the demands requested by the ship activity. The integration with the maritime system could be challenging for some reasons, however, thanks to the correct economic sustain, the studied solutions can be properly implemented, playing a key role in the ZHENIT project.

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