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

D 4.1 | KPI Definition and overall ZHENIT validation campaign strategy

WP4 – Validation Campaign (on board and at lab scale)

Version 1.6 / June 2024

HORIZON-CL5-2021-D5-01-10

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

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Document History

Project Acronym	ZHENIT
Project Title	Zero waste Heat vessel towards relevant Energy savings also thanks to IT technologies
Project coordination	RINA-C
Project duration	42 months – from 1/06/2022 to 30/11/2025
Title	D 4.1 KPI Definition and overall ZHENIT validation campaign strategy
Dissemination Level	PU - Public
Status	Final version for submission
Version	1.6
Work Package	WP4
Lead Beneficiary	RINA-C
Other Beneficiaries	
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Reviewers	UoB and TECNALIA

Date	Ver.	Contributors	Comment
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May 21st, 2024	1.2	Ane Bereciartua (TECNALIA)	Technical review
May 22nd, 2024	1.3	Felipe Trebilcock (TECNALIA)	Technical review
May 22nd, 2024	1.4	Andrea Frazzica (CNR)	Technical review
June 5th, 2024	1.5	Konstantinos Braimakis (NTUA)	Technical review
June 14th, 2024	1.6	Francesca DI GRUTTOLA (RINA-C)	Final review

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Table of Content

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List of Figures

List of Tables

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Abbreviation and Acronyms

Acronym	Description
AD	Adsorption Desalination
AM	Adsorption Machine
COP	Coefficient of Performance
EER	Energy Efficiency Ratio
HP	Heat Pump
HTF	Heat Transfer Fluid
HTHP	High Temperature Heat Pump
IE	Isobaric Engine
IEE	Isobaric Expansion Engine
IMO	International Maritime Organization
KPI	Key performance Parameter
LTES	Latent Thermal Energy Storage
MED	Multi-Effect Desalination
MSF	Multi-Stage Flashing
ORC	Organic Rankin Cycle
PCM	Phase Change Material
PSU	Practical Salinity Unit
SCP	Specific Cooling Power
SDWP	Specific Daily Water Production
SRC	Steam Rankine Cycle
STES	Sensible Thermal Energy Storage
TCS	Thermochemical Storage
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 (IMO) 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).

This document named Deliverable 4.1, based on Task 4.1 of ZHENIT project, deals with KPI Definition and overall ZHENIT validation campaign strategy. The objective of the deliverable is to select and define the most prominent parameters for the interpretation of the performances of the WHR technologies studied and purposed for the testing campaign at laboratory scale, replicating the working conditions of different types of vessels. Moreover, this document aims to set the validation campaign strategy, offering a clear methodology to follow for the clarification of the results and precise guidelines about the daily scheduling of the operations during the testing campaign.

This report analyses requirements and principles to adopt on field, creating a wide range of scenarios in order to cover all the possible configurations of the hosen technologies, which are: ORC-ejector HP system, TES system, Adsorption Machine, Isobaric Expansion Engine. Additionally, an integrated solution system including TES is studied. Thanks to this report, the tester arranges a complete set of KPIs to monitor during the experiments, following a precise guideline covering all the possible solutions presented by ZHENIT project for the Waste Heat Recovery.

The operating conditions of each machine involved in the testing campaign have been created by the theory available at the current state of ZHENIT's advancement (M25). Therefore, the values mentioned related to each technology could be subjected to review under the practical testing phase by the tester, according to the specific conditions of the laboratory.

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1 Introduction

This deliverable is named “KPI Definition and overall ZHENIT validation campaign strategy” and it constitutes the D4.1 of the ZHENIT project, prepared in the framework of Work Package 4 and delivered at M25.

The aim of this task is to define the KPIs that will be used for the evaluation and validation of both, the individual technologies as well as the integrated system that will form the ZHENIT concept and to prepare the required validation campaign strategy and representative testing scenarios. The technologies involved in the study are the Organic Rankine Cycles (ORC), Thermal Energy Storage (TES), Sorption Desalination & Refrigeration and Isobaric Expansion Engines (IEE). This document will validate the integration of these machines at laboratory scale and subsequently at vessel scale, replicating the testing campaign in the pilot vessel chosen by the consortium. The details about the pilot vessel are presented in Annex A.

The definition of Key Performance Indicators (KPI) consists in the choice of the most representative physical quantities for the analysis of Waste Heat Recovery technologies already presented. The main interest is to create a list of parameters to monitor during the experiments that will be performed at laboratory scale and on-board. The validation campaign strategy aims to set the conditions to follow during the experiments, creating an easy methodology that investigates all the possible solutions in the machine operational structure.

The deliverable encompasses the evaluation of many physical quantities, requiring a validation methodology to test effectively the desired parameters with low margin error, good affordability and safety. A list of equipment is analyzed for each technology, aiming to explain the correct positioning of the instruments and their output. In order to enhance the testing phase, a scheduling of the number of tests to conduct is provided. According to the operational boundaries of laboratory and on-board vessel, the work subdivides the tests into different scenarios with the objective of covering many operational fields of each single machine and their integration.

The analysis depends on a specific scheme which characterizes the temperature profile of the waste heat and the design of the technologies. This scheme constitutes the first point to set the key parameters and define the testing scenarios, describing the operational boundaries. The scheme is reported in Figure 1-1, and represents a basic reference for the following discussions.

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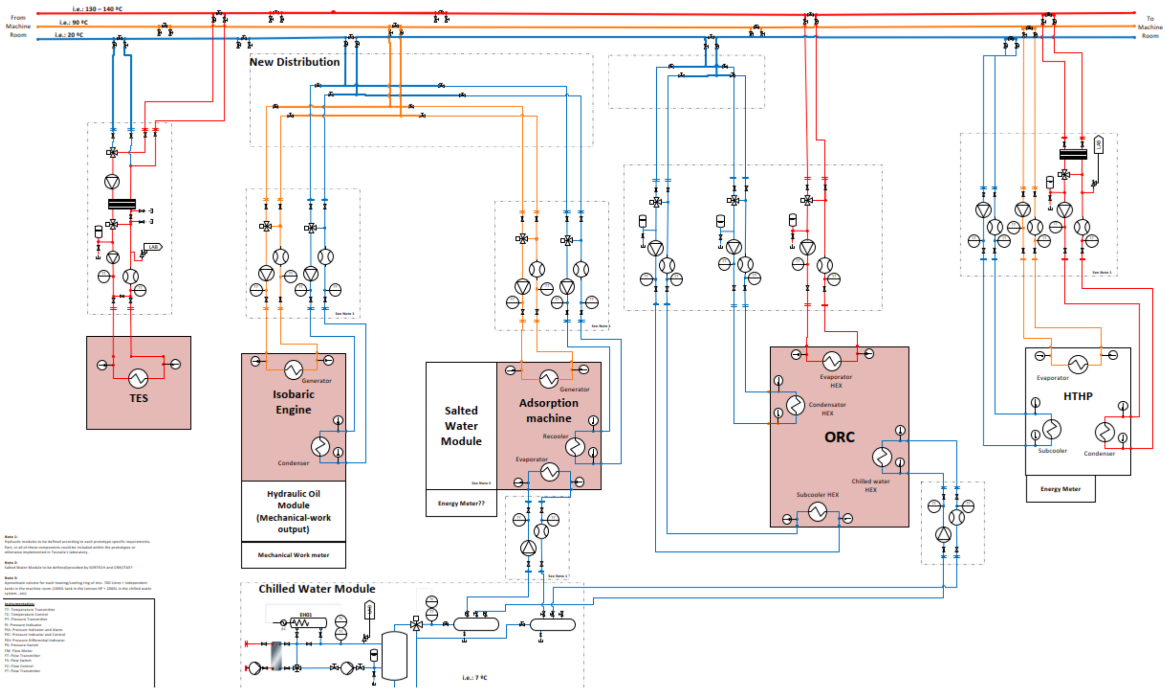

Figure 1-1: Scheme of LAB technologies.

The present deliverable is divided per technology and structured as follows:

- Chapter 1: Introduction;
- Chapter 2: Methodology;
- Chapter 3: Organic Rankine Cycle;
- Chapter 4: Thermal Energy Storage;
- Chapter 5: Sorption Desalination & Refrigeration;
- Chapter 6: Isobaric Expansion Engine;
- Chapter 7: Testing Scenarios;
- Chapter 8: Conclusions;

The Chapter named “Methodology” comprehends a guideline on the laboratory setting in the context of control architecture and safety requirement and a general description of the reference vessels used to replicate the working conditions in the laboratory, including the impact of the e-Sail technology.

Starting from this point, each chapter is subdivided into four sections:

- Technology Presentation, which contains the description of the technology and its settings at lab-scale;

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- KPIs, which contains the list of KPI to monitor relatively to the technology in issue and their definitions;
- Validation Campaign Strategy, which contains the adopted strategy to evaluate the KPIs, thus comprehending the list of the equipment needed and the key steps to perform correct and robust measurement, and the methodology to validate the obtained results.

Testing Scenarios is the chapter dedicated to the scheduling of the scenarios that investigate the different vessels configurations according to each technology. The total number of tests and the specific energy conditions will be provided case by case.

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2 Methodology

2.1 Laboratory Settings

This section aims to provide a guideline for the common practices developed for the different technologies involved in the testing campaign. In particular, the focus is on the control architecture of the prototypes and the safety requirements for the operational practices. The laboratory testing campaign will provide useful indications for the replication aboard the pilot vessel.

The instrumentation required has the objective to monitor all the physical parameters that give ideas about the performance and the improvements that the waste heat technologies create with respect to the baseline. The principal quantities to be evaluated are temperature levels, mass flows from different nets, energy values in crucial points of a specific cycle. The monitoring is dependent on an architecture which has to be defined before the start of the validation campaign. Figure 2-1 describes the boundaries and the connections in the Tecnalia's network, showing the role of each control device.

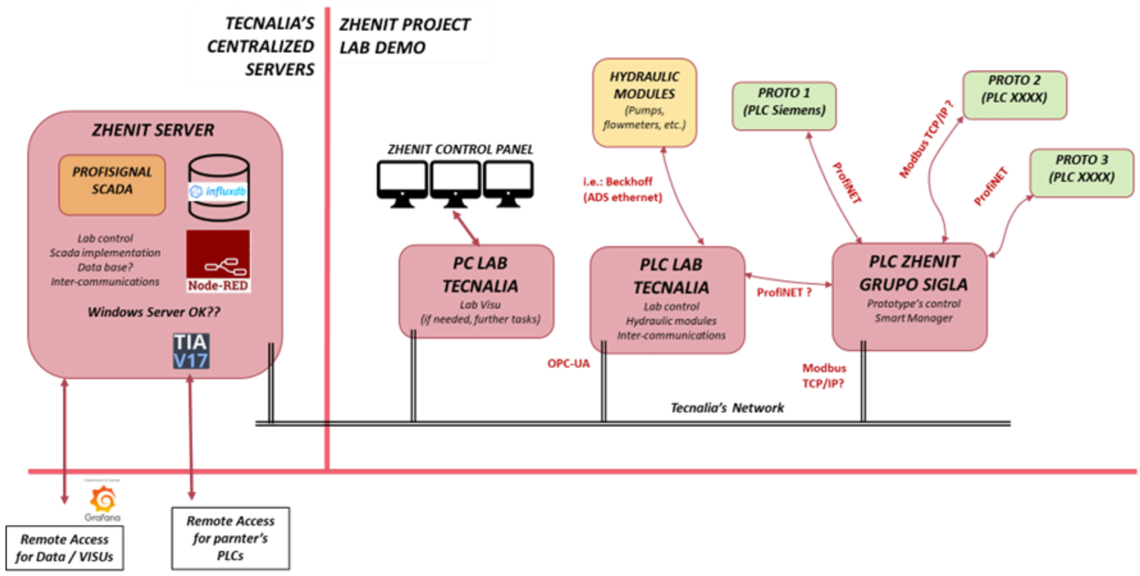

Figure 2-1: Control architecture of Tecnalia's Lab

Regarding the commissioning of the technologies, each partner will be responsible for its technology. For what concerns the operations, Tecnalia will provide remote access to Data and partner´s PLC for maintenance purposes. Each technology provider will create the devices control. Gruppo Sigla will develop the integrated system control for the validation of the ZHENIT validation campaign, based on a Smart Control System for maximizing the energy savings.

2.2 Safety Requirements

The strategy for the validation campaign at laboratory scale suggests the consultancy of **safety requirements**. Here is a list of the most common safety requirements needed:

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- Training of the personnel
- Protective equipment
- Emergency procedures
- Inspection of the monitoring equipment
- Detection of potential leak or emission points
- Remote access for data monitoring

The documentation required for each of the technologies includes an operation and maintenance manual, an electrical diagram, relevant for addressing any electrical issues, and a safety and/or risk assessment analysis, as mandated by Tecnalia's Quality Department to ensure adherence to safety standards.

2.3 Validation Guidelines

It is necessary to provide some solid guidelines for the validation of the results obtained from the measurements to interpret the characteristics of the machinery in relation to the originated waste heat. A list of operations is created to be adopted on site aiming to enhance the KPIs analysis.

- Accuracy Assessment: In addition to comparing experimental results with theoretical calculations, statistical methods can be used to quantify the degree of agreement between two sets of data. This could include the calculation of error metrics such as mean absolute error and root mean square error.
- Performance Mapping: Along with identifying optimal operating conditions, the creation of maps helps to understand how variations in operating conditions affect performance metrics.
- Component testing: In addition to comparing experimental results with manufacturer specifications or theoretical models, the conduction of component-level sensitivity analyses is useful to assess the sensitivity of key performance indicators to variations in component parameters. The validation of the performance of each component under a range of operating conditions ensures robustness across different scenarios.
- Sensitivity Analysis: Expanding the sensitivity analysis includes probabilistic methods such as Monte Carlo simulation to assess the likelihood of different outcomes under varying degrees of uncertainty. The validation of the results of the sensitivity analysis by comparing them with experimental data or expert judgments allows testers to identify that sensitivities are realistic and meaningful.

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2.4 Type of Ship Prototypes Description

A Cargo Vessel is a type of ship designed primarily for the transportation of goods and commodities across maritime routes. Cargo vessels are often larger in size and have a higher cargo capacity compared to other types of ships. This means they require more propulsion power to move efficiently through the water, especially when fully laden. Cargo vessels commonly utilize diesel engines for propulsion. These engines can vary in size and configuration depending on the size of the vessel and the power required. Some larger cargo ships may even have multiple engines or auxiliary power units to meet their energy demands. Cargo vessels often operate on fixed routes and schedules, which allows for optimization of fuel consumption through efficient route planning and speed adjustments. Cargo vessels lengths depend primarily on their operational functionality: small coastal cargos may reach a maximum of 100 m, while bulk cargos specialized in container's shipping or tankers may touch the 400 m.

Ferries are specialized vessels designed for the transportation of passengers, vehicles, and sometimes cargo across bodies of water, such as rivers, lakes, or seas. They come in various sizes and configurations to accommodate different routes, passenger capacities, and types of vehicles. For instance, smaller passenger ferries are typically used for short-distance crossings, such as river crossings or shuttles between islands. They may have lengths ranging from around 20 meters to 50 meters, with open deck spaces for passengers to embark and disembark. Larger ferries may operate on longer routes with higher passenger volumes. They may have lengths ranging from 50 meters to 100 meters, suited for cabins, seating areas, cafeterias, and vehicle decks. Catamaran ferries feature two parallel hulls connected by a deck or superstructure. They offer increased stability and speed compared to conventional monohull ferries. They are often used for high-speed passenger transport on coastal routes.

Cruise ships are large passenger vessels designed for leisure travel and entertainment, offering passengers a luxurious and immersive experience while exploring various destinations around the world. They come in various sizes and configurations to accommodate different passenger capacities, amenities, and itineraries. For example, mega-cruise ships are the largest and most luxurious cruise ships, capable of accommodating thousands of passengers and offering a vast array of onboard amenities and entertainment options. They may have lengths exceeding 300 meters, with beams typically between 40 meters to 60 meters or more. Mega-cruise ships feature multiple decks with restaurants, bars, theaters, shopping arcades, swimming pools, spas, sports facilities, and other recreational amenities.

Different typologies of vessel are characterized by different loads and so different waste heat quantities. The waste heat temperature profile depends mainly on the engine specifications, the ship's route and the energy demand. Cargo Vessels are not designed to treat passengers like a Cruise, assessing a specific sailing scheme, meaning that the energy profile but also auxiliaries and mechanical integrations will be different. One common feature between the three types of vessels is the trend of temperature profile, which assumes the evolution of a constant over time.

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One important validation scenario of the testing campaign is the presence of e-Sail, which is an innovative auxiliary source of propulsion system able to contribute to energy savings. The e-Sail operation brings about two potential modifications to the vessel's operation. Firstly, in favorable wind conditions, the device generates positive power, allowing a reduction in the main engine's power output. Conversely, in unfavorable wind conditions, the e-Sail generates negative power, requiring the main engine to compensate with higher power output to maintain vessel speed. This scenario leads to an increase in available heat. During the experiment campaign it is fundamental to test the demand values for different vessels relative to the presence of this device. In case of positive wind conditions, e-Sail contributes to savings in propulsion and consequently in primary energy demand, but it impacts only on the main engines of the vessel and not on auxiliaries. The e-Sail analysis comprehends an elaboration of the results obtained during the laboratory validation campaign and it will focus on different propulsion savings conditions for the three different vessels. The vessel typology and the wind profile could be important factors influencing the data analysis, so the testing scenarios energy assessment analysis should account the e-Sail presence as a theoretical variable in the results validation.

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3 Organic Rankine Cycle

3.1 Technology presentation

In the ZHENIT project, an ORC-ejector integrated heat pump prototype will be developed. The prototype consists of a parallel ORC- parallel/serial ejector-vapor compression cycle (EVCC) layout (Figure 3-1) operating with R1233zd(E). All technical details about the prototype are provided in Deliverable D2.3. In this report, only the most essential information related to KPI assessment is presented.

The prototype has the following operating modes:

1) Electricity-only mode through the operation of a recuperative Organic Rankine Cycle (ORC). In this mode, heat is supplied to the prototype and electricity is produced.
2) Combined heat and power (CHP) mode through the operation of a non-recuperative ORC. In this mode, heat is supplied to the prototype and is converted to electricity and useful heat.
3) Combined power and cooling mode (CCP) through the simultaneous operation of an ORC and the EVCC. In this mode, heat is supplied to the prototype along with electricity, which is used for driving the EVCC. Meanwhile, through the operation of the prototype, electricity and cooling is produced.

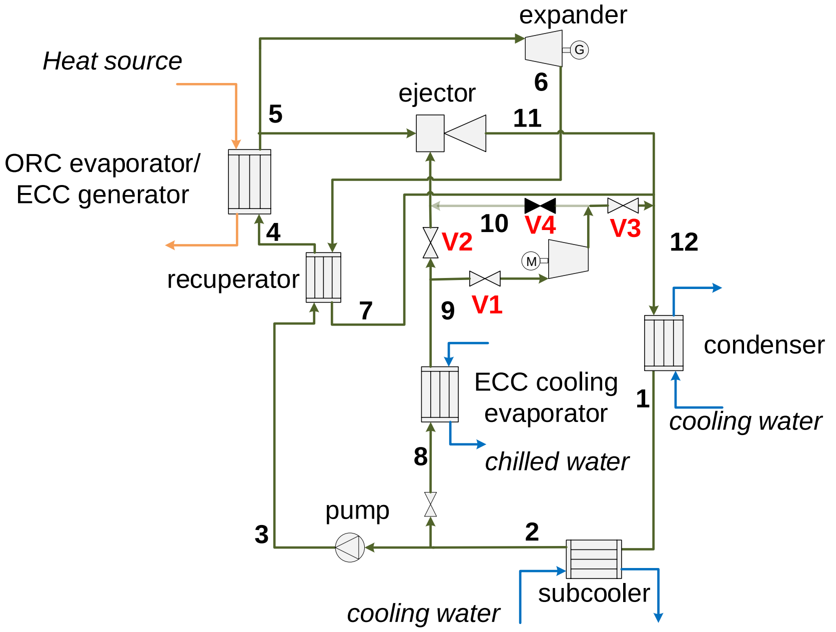

Figure 3-1: Scheme of ORC-ejector integrated heat pump

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The system is composed of a generator heat exchanger connected to high-level temperature line (about 140°C), while the condenser and a subcooling unit are connected to the low-level temperature line (about 20°C). A heat exchanger is linked to the chilled water circuit, which provides freshwater at about 10°C. In Table 3-1 the technical specifications of the Trigenerative WHR ORC-HP solution are reported.

Table 3-1: Trigenerative WHR ORC-HP specifications

ORC-HP circuit			
Unit	Inlet Water Temperature [°C]	Outlet Water Temperature [°C]	Thermal Power [kW]
ORC Evaporator	140	130	100
ORC Condenser	35-40	40/55	86.21 (min) - 91 (max)
ORC Subcooler	35-50	40/55	2.86 (min) - 3.01 (max)
HP Evaporator	15	10	2.2 (min) - 3.1 (max)
ORC-HP Mechanical Integration			
Presence of hydraulic modules	Yes		
Number of Hydraulic modules (critical)	4		
ORC-HP Electrical Integration			
Power Supply [kWe]	1.42 (max)		
Power generation [kWe]	11.32 (max)		
Presence of Inverter	Yes		

3.2 KPIs

During the testing phase for the ORC-ejector integrated heat pump prototype validation, a wide range of Key Performance Indicators will be calculated which are directly related to the operating modes that were described previously.

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ORC electric efficiency

An ORC will be operational in all three operating modes of the prototype. In this case, a relevant KPI is the ORC electric efficiency. The electric efficiency of an ORC is defined as the measure of how effectively the system converts input heat into electricity. It is typically expressed as a percentage, and higher values of efficiency are translated into higher machine's capability to exploit the available source of energy. The formula for calculating the thermal efficiency is showed by the following equation:

$$\eta_{e,ORC} = \frac{P_{e,net,ORC}}{\dot{Q}_{ORC,evap}}$$

Where:

$\eta_{e,ORC}$ is the electric efficiency and its unit of measure is the percentage [%];

$P_{e,net,ORC}$ is the net electric power output of the ORC system, defined as the difference between the gross electric power of the expander generator ($P_{e,exp}$) minus the electric power consumed by the pump motor ($P_{e,pump}$):

$$P_{e,net,ORC} = P_{e,exp} - P_{e,pump}$$

$\dot{Q}_{ORC,evap}$ is the heat supplied to the ORC system through the ORC evaporator/ECC generator of energy due to the source's pressure and temperature conditions, which enters the system at the evaporator level, and it is expressed in Joule or its multiples [J] or Watt-hours and its multiples [kWh]. It is calculated as described:

$$\dot{Q}_{ORC,evap} = \dot{m}_{hs}\left(h_{hs,in} - h_{hs,out}\right)$$

Where, $\dot{m}_{hs}$ is the mass flow rate of the heat source stream entering the ORC evaporator and $h_{hs,in} - h_{hs,out}$ is the enthalpy difference of the heat source stream at the ORC evaporator inlet/outlet.

ORC CHP efficiency

This CHP efficiency is related to the CHP operating mode of the system and expresses its overall efficiency, also taking into account the useful heat that is produced, according to the following equation:

$$\eta_{CHP,ORC} = \frac{P_{e,net,ORC} + \dot{Q}_{heat}}{\dot{Q}_{ORC,evap}}$$

The useful heating is equal to the heat recovered from the condenser of the system, described according to the following equation:

$$\dot{Q}_{heat} = \dot{m}_{w,cond}\left(h_{w,cond,out} - h_{w,cond,in}\right)$$

$\dot{m}_{w,cond}$ is the mass flow rate of the water entering the ORC condenser and $h_{w,cond,out} - h_{w,cond,in}$ is its enthalpy difference as it passes through the heat exchanger.

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EVCC thermal COP

In CCP operating modes, cooling is also produced. Two indexes are used for evaluating the performance of the system in that case. The first is the total thermal COP, which expresses the percentage of cooling output produced by the EVCC part of the prototype ($\dot{Q}_{evap,EVCC}$) divided to the thermal input to the system, according to the following equation:

$$COP_{th,total} = \frac{\dot{Q}_{evap,EVCC}}{\dot{Q}_{ORC,evap}}$$

The cooling output is derived from the energy balance in the cooling evaporator of the EVCC:

$$\dot{Q}_{evap,EVCC} = \dot{m}_{w,evap}\left(h_{w,evap,in} - h_{w,evap,out}\right)$$

$\dot{m}_{w,evap}$ is the mass flow rate of the water entering the EVCC cooling evaporator and $h_{w,evap,in} - h_{w,evap,out}$ is its enthalpy difference as it passes through the heat exchanger.

EVCC electrical COP

An additional KPI is the electrical COP of the EVCC. This is defined as cooling output produced by the EVCC divided by its electricity consumption (including the ORC pump and the compressor ($P_{e,comp}$). This index can be used to evaluate how much electricity is saved using the EVCC compared to the use of a standard vapor compression cycle (VCC) chiller.

$$COP_{e,EVCC} = \frac{\dot{Q}_{evap,EVCC}}{P_{e,pump} + P_{e,comp}}$$

Other relevant parameters

According to ORC, other important parameters to be studied are the **temperature** and the **mass flow**. In particular, the objective of a machine as ORC should be to build a temperature diagram to monitor the operating conditions at the critical working points (pump, evaporator, turbine, condenser). Moreover, the mass flow should help in the analysis of the fluid into the pipes, monitoring possible losses and allowing the calculations of many important data, as previously shown.

3.3 Validation Campaign Strategy

The primary objective of the validation campaign strategy is to verify the performance of the ORC-ejector integrated heat pump under its working conditions. The validation requires the analysis of the KPIs already described in the previous section. The aim is to deeply understand the inputs, the outputs, and the stability of the machine, adopting a correct system of calculus.

The strategy is based on measuring the lengths previously discussed, thanks to the auxilium of specific instruments. The equipment needs to be set up according to the real conditions of the laboratory, respecting constraints, and protocols.

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The **equipment** needed for the validation campaign of ORC is here listed:

Electrical Power Meters

These instruments can measure directly the electricity produced by the ORC-ejector integrated heat pump, monitoring the electrical output. The electrical power meter is typically connected to the generator, which is linked to the expander. It provides real time measurements of the net electrical power produced. It should be installed in a suitable location for the electrical circuit, typically at the output terminals of the generator. It should ensure a proper electrical connection and pre-set calibration, in order to avoid interferences and maintain good precision.

Data Acquisition System

A data acquisition system can be used to collect and analyze electrical signals from sensors and instruments, including those monitoring the power input to the pump or the turbine. The DAS can be configured to continuously monitor and record the power consumption of the pump or the expander, allowing for detailed analysis of its performance over time. It can be integrated with other power meters, to provide continuous and precise monitoring.

Thermocouples or Thermistors

Thermocouples and Thermistors are two devices adaptable for temperature measurement. The temperature sensors will be installed in the hydraulic circuit at the inlet and outlet of all heat exchangers of the prototype. These will allow the measurement of the temperature of the water flows leaving and entering the heat exchangers of the prototype, which is necessary to calculate the heat input to the ORC, the useful heating that is produced in CHP mode, as well as the cooling output in CCP mode. In particular, the temperature sensors must be placed at the inlet and outlet of the prototype ORC evaporator/ECC generator, at the inlet and outlet of the condenser and at the inlet and outlet of the EVCC cooling evaporator.

Flowmeters

Measuring the mass flow is fundamental for calculating the KPIs of ORC ejector-integrated heat pump. Flowmeters are devices specifically designed to measure the flow rate of a fluid. There are various types of flowmeters available, including:

- Differential pressure flowmeters (e.g., orifice plates, venturi meters, and flow nozzles), which measure the pressure drop across a restriction in the flow path to determine the flow rate;
- Electromagnetic flowmeters, which use Faraday's law of electromagnetic induction to measure the velocity of a conductive fluid flowing through a magnetic field;
- Ultrasonic flowmeters, which use ultrasonic waves to measure the velocity of a fluid flowing through a pipe.

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The flow meters will be placed in the hydraulic circuit to measure the flow rate of the water streams entering the heat exchangers of the prototype. Like the temperature sensors, this is necessary to calculate the heat input to the ORC, the useful heating that is produced in CHP mode, as well as the cooling output in CCP mode. Three flow meters are needed for measuring the flow rate of the water entering the ORC evaporator/ECC generator, the condenser and the EVCC cooling evaporator.

The expected contribution of **Primary Energy Saving** of the ORC ejector-integrated heat pump is estimated to be between 7% and 9% with respect to the baseline. For the calculation of primary energy savings, the focus should be on comparing the energy produced by the ejector-integrated heat pump prototype system directly to the energy that would have been generated by conventional systems such as a fossil fuel-based power plant like a diesel generator (for electricity and heating) and a conventional electricity-driven VCC chiller for cooling.

Here are the steps for accurately calculating primary energy savings:

- Determine the power generation, heating output or cooling capacity of the ORC system, typically provided in kilowatts (kW) or megawatts (MW).
- Estimate the annual energy production by multiplying the system's capacity by the number of hours it operates annually to produce electricity, heating and cooling, obtaining the total energy produced by the ejector-integrated heat pump in megawatt-hours (MWh) per year.
- Calculate the total primary energy consumption that would have occurred if the energy generated by the ORC system had been produced by the conventional method, reporting the result in kWh or MWh per year. This can be done by estimating the amount of energy that would have been required to generate the same amount of electricity using the conventional diesel generator (electricity), a boiler (heating) and an electricity-driven VCC chiller (cooling).
- Determine the primary energy savings simply by subtracting the ORC-ejector integrated heat pump system's primary energy consumption from the conventional method's primary energy consumption.

Finally, this section provides the settings for the **validation strategy** for ORC-HP System, here numbered pointing out the key steps:

[1] Define Validation Criteria:

- For the KPIs already mentioned (ORC electrical efficiency, ORC CHP efficiency, EVCC thermal COP, EVCC electrical COP), achieve a minimum theoretical value as determined by calculations or simulations, typically based on specific design targets.

[2] Validation Procedure:

- Operate the system under various heat source temperatures, mass flow rates, and other relevant parameters while measuring both the heat input, power output, heating output

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and cooling output (depending on the operating mode). Calculate the thermal efficiency based on these measurements and compare it against the specified minimum efficiency target.

[3] Data Analysis and Validation:

- Analyze Data: Analyze the collected data to evaluate the ORC ejector-integrated heat pump system's performance against the defined validation criteria for each KPI. Use statistical methods and modeling techniques to assess the accuracy and reliability of the measurements.
- Comparison: Compare the measured values of thermal efficiency, heat recovery effectiveness, and heat output with the specified targets or limits to determine compliance. Identify any discrepancies or deviations that may indicate performance issues or areas for improvement.
- Iterate and Optimize: Iterate on the validation procedure as necessary to address any discrepancies or optimize performance monitoring. Adjust operating parameters, measurement techniques, or testing protocols as needed to improve accuracy and reliability.

[4] Documentation and Reporting:

- Document Procedure: Document the validation procedure, including test setup, measurement techniques, and results. Maintain detailed records of all data collected during the validation process.
- Prepare Report: Prepare a validation report summarizing the findings, including comparisons of measured values to specified criteria, any deviations from targets, and recommendations for improvement. Provide clear and concise explanations of the validation methodology and results.

[5] Iterate and Improve:

- Continuous Improvement: Continuously refine the validation strategy based on feedback, new insights, and evolving system requirements. Incorporate lessons learned from validation tests to enhance the performance monitoring process and ensure ongoing compliance with KPIs.

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4 Thermal Energy Storage

4.1 Technology presentation

Thermal Energy Storage (TES) addresses the gap between thermal energy generation and demand, enhancing system efficiency. TES comes in three types: Sensible Thermal Energy Storage (STES), which increases material temperature without phase change, using common materials like water or molten salts; Latent Thermal Energy Storage (LTES), utilizing phase change materials (PCMs) to absorb and release heat during phase transition, offering higher energy density than STES; Thermochemical Energy Storage (TCS), employing reversible chemical reactions to absorb and release heat, with potential for high energy density but less mature compared to STES and LTES. TCS utilizes compounds like zeolites or salt hydrates. Each TES type has distinct advantages and applications, contributing to efficient energy management.

The TES system to be tested in the Tecnalia laboratory was designed based on a parametric analysis conducted by varying plate number, length and height. The model is based on the LTES system, where the PCM is subjected to the HTF dynamic across 10 steel plates. Regarding geometrical specifications, the plate length and height have been assigned in the range from 0.5 to 1.5 m with intervals of 0.025 m, while the number of plates has been set in the range from 6 to 12 with steps of 2 units. The distance amongst adjacent plates was kept fixed to 40 mm due to the manufacturing constraints imposed by the supplier. Thus, the width of the plate bundle of the configurations analyzed is in the interval between 0.34 and 0.64 m. The schematic of the TES geometry is visible in Figure 4-1 and the parameters considered in the parametric analyses are defined in Table 4-1.

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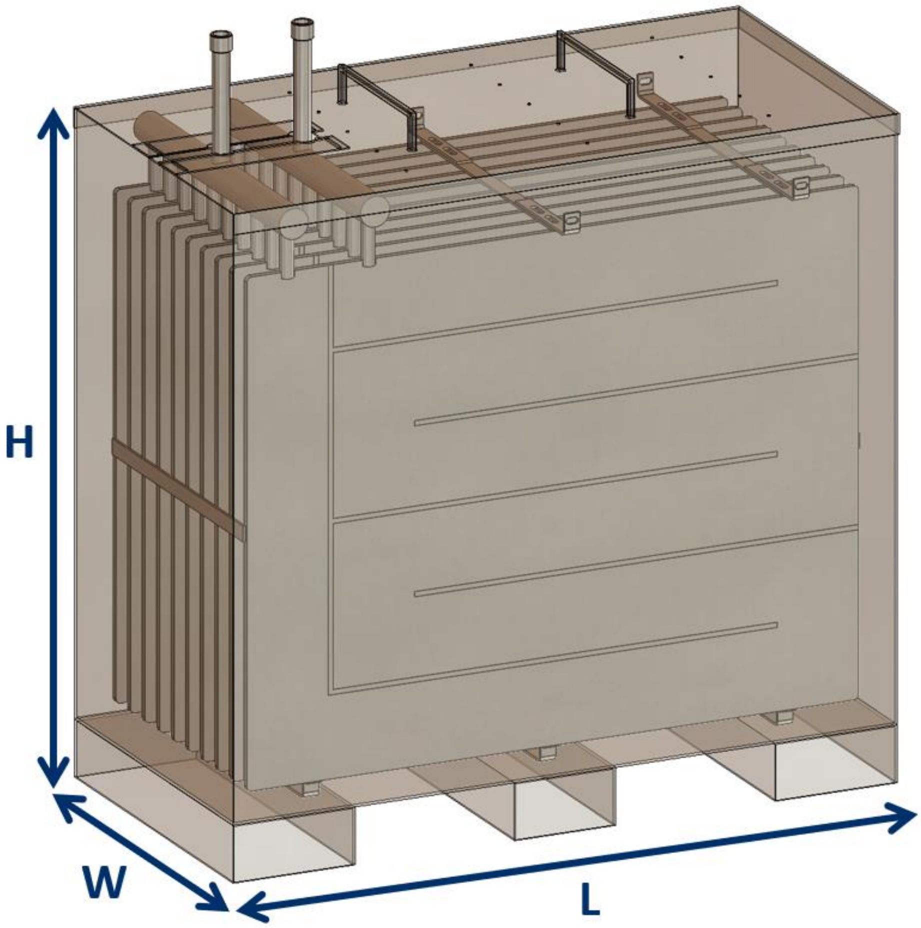

Figure 4-1: TES schematic figure.

Table 4-1: TES geometric specifications

Geometric parameter	Symbol	Value	Unit
Plate length	L	0.50 – 1.50	m
Plate height	H	0.50 – 1.50	m
Width	W	0.34 – 0.64	m
Plate number	N_p	10	-
PCM thickness	b	0.040	m

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Geometric parameter	Symbol	Value	Unit
HTF thickness	b_f	0.010	m

The specifics of the TES system used for this application are shown in Table 4-2.

Table 4-2: TES Technical Specifications.

TES phases			
Unit	Inlet Water Temperature [°C]	Outlet Water Temperature [°C]	Average thermal Power [kW]
Charging	90	70	3
Discharging	70	90	
TES Mechanical Integration			
Presence of hydraulic modules	Yes		
Number of Hydraulic modules (critical)	1		
TES Electrical Integration			
Power Supply [kWe]	N.A.		
Presence of Energy Meter	Yes		

4.2 KPIs

The TES system performance is evaluated through a list of KPIs which is described below.

Roundtrip Efficiency

Roundtrip Efficiency refers to the efficiency of storing and retrieving thermal energy within the LTES system. This KPI is calculated similarly to other energy storage systems but tailored to its specific characteristics. It involves measuring the energy input required to charge the system (such as heating the phase change material to its melting point) and the energy output obtained during discharge (such as extracting heat from the material as it solidifies), accounting for losses during both processes. Factors influencing the roundtrip efficiency of LTES include the intrinsic properties of the phase change material

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used (such as its specific heat capacity and latent heat of fusion), the efficiency of the heat transfer mechanisms within the system, and any losses due to heat leaks or other inefficiencies. The formula used for the calculation of Roundtrip Efficiency is the following:

$$\eta_{rt} = \frac{Q_{out}}{Q_{in}}$$

Where:

Q_{in} is the energy input required for the charging phase;

Q_{out} is the energy output released during the discharge phase.

In general, for the heat transfer calculation in TES, the formula used follows the calorimetry law, which can be expressed as:

$$Q_x = \dot{m}_x * c_p * (T_x - T_0) * \Delta t_{(dis)charge}$$

Where the subscript *x* refers to the charge phase or the discharge phase, and so the heat in input or the heat in output. The term $\dot{m}_x$ stands for the mass flow at *x* condition, measured in [kg/s]; c_p indicates the specific heat capacity of the HTF used in the system and it expressed in [J/kg°C]; $(T_x - T_0)$ is the temperature difference in [°C] between the initial condition at time zero and time *x*; $\Delta t_{(dis)charge}$ is the time in [s] required for the charge or the discharge phase, depending on the target heat.

Self-Discharging Time

Self-discharge time refers to the period it takes for an energy storage system to lose a certain percentage of its stored energy when it is not being actively charged or discharged. For example, if an LTES system has a self-discharge time of 10 days, it means that after 10 days of being fully charged and left unused, the system would have lost a certain percentage of its stored thermal energy. Self-discharge time is influenced by many factors, such as the properties of the storage medium, the insulation effectiveness, the ambient temperature, and the design of the storage system. Lower self-discharge times are preferable as they indicate higher efficiency and better retention of stored energy over time.

Power Limit

The power limit of a TES system refers to the maximum rate at which energy can be stored or discharged from the system. It represents the maximum power that the system can handle without experiencing adverse effects, such as overheating, degradation or loss of efficiency. It can be practically observed through the validation campaign after several measurements, corresponding to the maximum value of energy output. The power limit can be influenced by various factors including:

- Heat transfer rate, which is the capability to transfer heat to or from the PCM influences the maximum rate at which energy can be stored or discharged;
- Thermal conductivity of the PCM, indeed higher thermal conductivity can increase the power limit of the system;

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- Design of heat exchangers, which refers to the geometry of heat exchangers used to transfer heat to or from the PCM and that can affect the power limit;
- Operating temperature range, which is the temperature range over which the PCM can effectively store and release thermal energy impacts the power limit;
- Integration with other components.

Storage Duration and Capacity Utilization

Storage Duration refers to the length of time that an LTES system can effectively store thermal energy before it needs to be discharged or recharged. The storage duration depends on several factors, such as the amount of energy stored, the rate of energy discharge, the thermal properties of the PCM, and the efficiency of heat transfer mechanisms. Longer storage durations are desirable for applications where energy needs to be stored during periods of low demand and released during peak demand periods or, for instance, when intermittent renewable energy sources are unavailable, if considering a smart grid application.

Capacity Utilization measures the extent to which the storage capacity of an LTES system is being utilized over a given period. It is typically expressed as a percentage number, and it is calculated by comparing the actual energy stored or discharged from the system to its maximum storage capacity.

$$C_U = \frac{Actual\ Energy\ Stored/Discharged}{Maximum\ Energy\ Stored/Discharged} * 100\%$$

Higher capacity utilization indicates that the system is effectively storing and releasing energy as needed, maximizing its operational efficiency. Factors that affect capacity utilization include the energy demand profile, system design, control strategies, and the availability of excess energy for charging the storage system.

4.3 Validation Campaign Strategy

This section wants to show the necessary equipment to perform the monitoring of the KPIs previously described, explaining the positioning of the various instruments and their final output. The validation strategy offers a guide to follow during the operations for supervising the test with scientific affordability.

Here is a list of the equipment required for the validation campaign of Thermal Energy Storage:

Flowmeters

Flowmeters are necessary to measure and validate the mass flow $\dot{m}_{in}$ and $\dot{m}_{out}$ respectively entering and existing the system, allowing the calculation of the heat transferred by the HTF and so the Roundtrip Efficiency.

Flowmeters could be installed at the inlet and outlet of the heat exchangers, where the heat transfer fluid enters and exits the TES system; if feasible, additional flowmeters could be installed at various points along the piping network to monitor flow rates and detect any flow variations or anomalies.

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Thermocouples or Thermistors

Thermocouples and Thermistors are two sensors capable of measuring temperature. They are crucial for monitoring the inlet and outlet temperature T_{in} and T_{out} of the HTF, allowing the measurement of the Roundtrip Efficiency.

Those temperature sensors can be placed inside the PCM container at multiple locations to monitor the temperature distribution throughout the PCM during charging and discharging cycles. This provides insight into the thermal performance and effectiveness of the PCM. Other suitable system locations are at the inlet and outlet of the heat exchangers, to measure the temperature of the HTF entering and exiting the TES system. A possible use of the instruments can also be for evaluating the temperature gradient profile inside the PCM container: this can be realized through the installation of thermocouples or thermistors at different heights or depths.

Another use of thermocouples and thermistor is for the monitoring of ambient temperature surrounding the TES and monitoring the effect of the storage on the external environment.

Moreover, the temperature sensors are crucial for the evaluation of another KPI: the Self-Discharge Time. When measuring the self-discharge time, it's fundamental to calculate the temperature of discharge. This temperature serves as an indicator of the remaining thermal energy within the system. As the system self-discharges, the temperature gradually decreases over time, reflecting the release of stored thermal energy. By continuously monitoring the temperature of discharge, it can be accurately quantified the rate at which the TES system loses stored thermal energy. This information is essential for determining the self-discharge time, which represents the duration required for the stored energy to decrease to a specific level.

The temperature should be monitored also to avoid pressure failures during the start-up phase. A hydraulic module is essential to maintain the required charging and discharging temperatures of 90°C and 70°C, respectively. During the start-up of the TES system, it's crucial to prevent sudden pressurization by gradually increasing the temperature and pressure levels. It's important to adhere to the maximum allowable pressure rise of 1.0 bar per second.

Power Meters or Energy Meters

Power meters and Energy meters are two essential instruments for the validation of parameters such as the Power Limit. A power meter keeps track of the immediate power input or extraction rate to or from the TES system during experiments, aiding in determining the maximum power limit through instantaneous sampling. On the other hand, an energy meter measures the total energy stored or discharged by the TES system over a specific period, which integrates power over time and provides cumulative energy consumption or production data. When combined with other instruments like temperature sensors and flowmeters, this approach provides thorough data collection, facilitating an accurate analysis of the TES system's performance and the determination of its performance. Energy meters are also important for the evaluation of storage capacity and consequently capacity utilization:

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to calculate capacity utilization in a TES system, an energy meter is required to measure total energy stored or discharged and information about the maximum storage capacity of the system.

The proper location to install those devices has to be compatible with the TES system. In particular, the power meter should be placed in-line with the electrical power supply system, ideally near the power source or control panel. Regarding the energy meter, a suitable position should be near the power meter or integrated into the system's electrical circuitry. Ensure that the energy meter accurately captures the energy stored or discharged by the TES system over the specific period of interest.

The strategy for validating the KPIs involves calculating the **primary energy savings** facilitated by TES, which serves as a viable alternative to traditional boiler in terms of performance and energy capacity. TES leverages storage capabilities to mitigate energy losses and conserve primary energy resources. The expected primary energy saving contribution of TES is between 5% and 7%. The key steps in this validation process are outlined as follows:

- Identify the thermal energy storage capacity of the TES system, typically measured in kilowatts (kW) or megawatts (MW).
- Estimate the annual energy savings facilitated by the TES system by comparing its energy consumption with that of a traditional heat exchanger.
- Multiply the TES system's capacity by the number of hours it operates annually to determine the total energy saved, expressed in kilowatt-hours (kWh) or megawatt-hours (MWh) per year.
- Depending on the energy source displaced by the TES system, assess the primary energy consumption per unit of energy generated by the boiler. For instance, if the TES system displaces electricity generation from a fossil fuel power plant, determine the primary energy consumption per kWh of electricity generated from that fossil fuel. Similarly, if the TES system displaces direct combustion of a fuel (e.g., natural gas, heating oil), determine the primary energy consumption per kWh of energy produced by burning that fuel.
- Determine the primary energy savings by subtracting the TES system's primary energy consumption from the conventional boiler's primary energy consumption.

The **Validation Strategy** for the KPIs calculation is here summed:

[1] **Define Validation Criteria:**

- Roundtrip Efficiency: Achieve a minimum value of roundtrip efficiency.
- Self-Discharge Time: Measure Self-Discharge Time under controlled conditions and compare it against specified limits (e.g., less than 1% of stored energy per day).

[2] Power Limit: Determine the maximum power input that the system can sustain without compromising performance or safety.

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- Storage Duration: Measure the duration for which the TES system can store energy effectively under specified operating conditions.
- Capacity Utilization: Achieve an average utilization rate of at least 80% over a specified period.

[3] **Validation Procedure:**

- For Roundtrip Efficiency: Charge and discharge the TES system multiple times under varying conditions while measuring energy input and output.
- For Self-Discharge Time: Fully charge the TES system and monitor temperature or energy loss over an extended period.
- For Power Limit: Gradually increase the power input or extraction rate to the TES system while monitoring temperature and system performance.
- For Storage Duration: Charge the TES system to full capacity and monitor the time it takes to reach specified energy storage levels.
- For Capacity Utilization: Measure total energy stored and discharged over a specific period and calculate capacity utilization.

[4] **Data Analysis and Validation:**

- Analyze the collected data to evaluate the TES system's performance against the defined validation criteria for each KPI.
- Compare measured values with specified limits or targets to determine compliance.
- Iterate on the validation procedure as necessary to address any discrepancies or optimize performance monitoring.

[5] **Documentation and Reporting:**

- Document the validation procedure, including test setup, measurement techniques, and results.
- Prepare a validation report summarizing the findings, including any deviations from specified criteria and recommendations for improvement.

[6] **Iterate and Improve:**

- Continuously refine the validation strategy based on feedback, new insights, and evolving system requirements.
- Incorporate lessons learned from validation tests to enhance the performance monitoring process and ensure ongoing compliance with KPIs.

Thanks to this approach, the monitoring and assessment of the TES performance will ensure reliability and effectiveness.

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5 Sorption Refrigeration & Desalination

5.1 Technology presentation

Sorption is a reversible thermochemical or thermophysical reaction used in various technologies for producing cold power, clean water, or both. Sorption involves a porous material capturing water vapor or gas and crystallizing it onto its surface. Depending on the physical phenomena, sorption is divided into two technologies: adsorption-based process and absorption-based process. Sorption refrigeration utilizes low evaporation temperatures achieved at low refrigerant partial pressures to extract heat from a fluid, achieving cooling effects. Sorption desalination involves evaporating, adsorbing, and desorbing seawater into and from a sorbent material to produce purified water. Integration of sorption refrigeration and desalination creates hybrid systems. An adsorption refrigeration and desalination process involve evaporators, absorber/desorber beds, and condensers. Desalination technologies include membrane desalination and thermal desalination methods like multi-effect desalination (MED) and multi-stage flashing (MSF). Membrane distillation (MD) operates on a partial pressure differential across a hydrophobic membrane, requiring lower heat and pressure. Sorption refrigeration and desalination can be advantageous in marine applications, providing cooling and freshwater production from waste heat regeneration.

The machine that will be used in the test exploits the adsorption technology, and it is composed of two parts: the salted water module and the adsorption machine, which comprehends a generator, connected to the medium-level temperature line, a recooler and an evaporator, both connected to the low-level temperature line. The evaporator is linked to the freshwater stream, which is stored in a circuit constituting the water sink for the other technologies. The technical specifications of the machine are presented in Table 5-1.

Table 5-1: Adsorption Machine technical specifications.

Adsorption Machine Specification			
Unit	Inlet Water Temperature [°C]	Outlet Water Temperature [°C]	Thermal Power [kW]
Generator	90	70	20
Recooler	25	35	30
Evaporator	15	10	10
Adsorption Machine Mechanical Integration			
Presence of hydraulic modules	Yes		

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Number of Hydraulic modules (critical)	3
Adsorption Machine Electrical Integration	
Power Supply [kWe]	3 (max)
Presence of Inverter	Yes

5.2 KPIs

The AM is a technology suited for several purposes. Its functions are monitored through many KPIs, which are reported below and constitute the approach for the performance evaluation.

COP and EER

Regarding adsorption desalination and refrigeration machine, the Coefficient of Performance (COP) is defined as a measure of the efficiency of the system in producing the desired refrigeration or desalination effect relative to the input energy or work required. The concept slightly differs considering desalination or refrigeration modality.

For adsorption desalination systems, the COP can be defined as the ratio of the heat extracted from the saline water to the heat input required to drive the adsorption process. It represents how much desalinated water can be produced per unit of energy input.

$$COP = \frac{|Q_{cool}|}{Q_{in}}$$

For refrigeration machines, the parameter takes the name of EER (Energy Efficiency Ratio), which is typically defined as tis the ratio of cooling energy over electricity required to operate the cycle (i.e. auxiliaries such as pumps, valves, etc.). This parameter indicates how much cooling can be achieved per unit of energy input.

$$EER = \frac{|Q_{cool}|}{W_{in}}$$

COP and EER are a value that typically exceeds 1. In both cases, a higher efficiency number indicates greater efficiency in achieving the desired outcome (desalination or refrigeration) for a given input of energy.

Q_{cool} can be measured at recooler level, obtaining the temperature delta between input and output and the mass flow. The formula is simply: $Q_{cool} = \dot{m}_{cool,in} * c_p * (T_{cool,in} - T_{cool,out}) * \Delta t_{cool}$

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Q_{in} and W_{in} should be measured by observing the temperature and mass profile at the generator level, where the waste heat enters the cycle, implying the monitoring of mass and temperature before and after the generator.

SCP

SCP is the Specific Cooling Power, and it represents the amount of cooling power per unit mass of sorbent. It is typically expressed in [kW/kg] and ruled by the formula below:

$$SCP = \frac{Q_{cool}}{m_{sorbent} * t_{cycle}}$$

Where $m_{sorbent}$ is the mass of the sorbent in [kg] and t_{cycle} is the cycle time in [s].

Desalination Energy Efficiency

The desalination energy efficiency corresponds to the energy required to produce a unit volume of freshwater. It is expressed by the following formula:

$$\varepsilon_{des} = \frac{W_{in}}{V_{freshwater}}$$

Where W_{in} is again the energy consumed by the desalination process, and $V_{freshwater}$ is the volume of freshwater produced. The unit of measure of this parameter is [J/m^3].

Salinity Reduction Efficiency

Salinity Reduction Efficiency represents the effectiveness of reducing salinity levels in seawater. It analyzes the salinity levels of the input seawater and the output freshwater to calculate the reduction efficiency. It is a percentage value coming from the following equation:

$$SRE = \frac{C_{in} - C_{out}}{C_{in}} * 100\%$$

Where C_{in} is the initial salt concentration of the feed water, and C_{out} is the final salt concentration of the product freshwater.

Specific Daily Water Production

Specific Daily Water Production (SDWP) refers to the amount of freshwater produced per unit of installed capacity of a desalination system over a specified period, typically measured on a daily basis. It is a key performance indicator used to evaluate the efficiency and productivity of desalination plants. The expression of SDWP, measured in [m^3/day /m^3_{max}] is:

$$SWDP = \frac{V_{freshwater}/day}{V_{max}}$$

Where V_{max} corresponds to the installed capacity of the desalination plant in [m^3].

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5.3 Validation Campaign Strategy

The testing campaign, as already seen, involves the use of specific instruments. Here is the List of equipment needed for Adsorption Machine test:

Flow Meters

Flowmeters can be utilized in the validation campaign to measure the flow rates of water, which is crucial for calculating the KPIs related to the process of freshwater production and refrigeration. Flowmeters are essential for measuring the flow rate of seawater entering the desalination unit. By combining flow rate data with measurements of energy input (e.g., electricity consumption), you can calculate the energy efficiency of the desalination process. Flowmeters provide the data needed to determine the total volume of water processed over a given period, allowing you to accurately calculate energy efficiency. Flowmeters are used to measure the total volume of fresh water produced by the desalination unit per day, allowing the monitoring of SDWP. It's essential to ensure that flowmeters are properly calibrated and maintained throughout the validation campaign. Additionally, flowmeter data should be collected consistently and synchronized with other relevant measurements for the assessment of the machine’s performance.

Thermocouples or Thermistors

Thermocouples or thermistors can be strategically positioned at key points within the refrigeration cycle to monitor temperatures. They can measure temperatures at the evaporator, condenser, adsorption/desorption chambers. These temperature measurements are essential for calculating COP and EER, as they provide data on heat input and output. Temperature sensors can also be used to monitor temperature changes within the desalination unit. By combining temperature measurements with flow rate data, it’s possible to calculate the energy efficiency of desalination.

Energy Meters

The installation of energy meters allows to measure the electrical power consumed by the adsorption refrigeration and desalination machine. Energy meters can be placed at the main power supply of the machine to capture the total energy consumption accurately. The collection of energy consumption data should be performed continuously or periodically during machine operation. By measuring this quantity, the evaluation of EER and desalination energy efficiency is a direct consequence, combining results with the instruments previously described.

Salinity Refractometers

Salinity refractometers are instruments that exploit the refraction principle to measure the salinity of water. They measure the change in the refractive index of a substance with varying solute concentration ruled by Snell’s law. As the salt concentration increases, the refractive index of the water increases too. This relationship between solute concentration and refractive index allows salinity refractometers to indirectly measure the salinity of a water sample by measuring its refractive index.

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The use of salinity refractometers allows to measure the salt concentration of both the inlet seawater and the outlet desalinated water. The sampling of water from the inlet and outlet of the desalination unit is important to analyze refractive indices using the refractometer. Salinity refractometers typically provide readings in Practical Salinity Units [PSU] or Parts Per Thousand [ppt]. The KPI directly affected by this instrument is the Salinity Reduction Efficiency.

Conductivity Meters

The salinity of water can be evaluated also by exploiting the conductivity of the salt. Conductivity meters operate based on the principle that the presence of dissolved ions in water enhances its ability to conduct electricity. When an electrical voltage is applied across two electrodes immersed in the water sample, ions in the water facilitate the flow of electrical current between the electrodes. By measuring the electrical conductivity of a water sample, conductivity meters can quantify the salinity of the water, typically expressed in practical salinity units [PSU] or parts per thousand [ppt]. This instrument represents an alternative to the salinity refractometer for the calculation of Salinity Reduction Efficiency.

The strategy for validating the KPIs involves the quantification of **primary energy savings** from the Adsorption Machine, which can constitute an alternative option to conventional desalination and refrigeration systems which can be Reverse Osmosis and Thermal Distillation through the utilization of gasoline. Adsorption Machine primary energy saving is estimated between 7% and 10%. The key steps in this validation process are outlined as follows:

- Identify the capacity of Adsorption Machine, typically measured in kilowatts (kW) or megawatts (MW), which indicates the capability to produce chilled water or provide cooling.
- Estimate the annual energy savings facilitated by the Adsorption Machine by comparing its energy consumption with that of a traditional vapor compression chiller.
- Multiply the Adsorption Machine's capacity by the number of hours it operates annually to determine the total energy saved, expressed in kilowatt-hours (kWh) or megawatt-hours (MWh) per year. This gives you a quantitative measure of the energy efficiency of the Adsorption Machine compared to conventional methods.
- Depending on the energy source displaced by the Adsorption Machine, assess the primary energy consumption per unit of energy generated or saved. For example: if the Adsorption Machine displaces electricity consumption from a fossil fuel power plant, determine the primary energy consumption per kWh of electricity generated from that fossil fuel; If the Adsorption Machine displaces direct combustion of a fuel (e.g., natural gas, heating oil) for cooling purposes, determine the primary energy consumption per kWh of energy produced by burning that fuel.
- The determination of the primary energy savings is completed by subtracting the Adsorption Machine's primary energy consumption from the conventional chiller' or osmosis system primary energy consumption.

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Again, it is important to call out the main criteria for the **validation** of the KPIs monitoring:

[1] Define Validation Criteria:

- Coefficient of Performance (COP): Achieve a minimum COP value as determined by theoretical calculations or simulations, typically based on the ratio of useful output (desalination or refrigeration) to the required input (energy or heat).
- Energy Efficiency Ratio (EER): Measure the energy efficiency of the AM system by comparing the useful output (desalination or refrigeration) to the total energy input. Achieve a minimum EER value to ensure efficient operation.
- Desalination Energy Efficiency: Ensure efficient utilization of energy for desalination by achieving a high energy efficiency ratio for the desalination process, taking into account factors such as specific energy consumption per unit of fresh water produced.
- Salinity Reduction Efficiency: Measure the effectiveness of the desalination process by quantifying the reduction in salinity or salt concentration in the feedwater compared to the product water.
- Specific Cooling Power (SCP): Achieve a specified SCP value to ensure effective refrigeration performance, typically measured as the amount of cooling produced per unit mass of adsorbent material per unit time.
- Specific Daily Water Production (SDWP): Achieve a minimum SDWP value to ensure adequate freshwater production capacity per unit time, considering factors such as system throughput and cycle time.

[2] Validation Procedure:

- For COP and EER: Operate the AM system under various operating conditions (temperature, pressure, flow rates) while measuring energy input and output. Calculate COP and EER based on the measured data and compare them against the specified minimum values.
- For Desalination Energy Efficiency: Conduct tests to measure the energy consumption of the desalination process and the amount of fresh water produced. Calculate the energy efficiency ratio for desalination and compare it against the required efficiency target.
- For Salinity Reduction Efficiency: Measure the salinity or salt concentration of the feedwater and product water before and after desalination. Calculate the percentage reduction in salinity and ensure it meets the specified efficiency requirements.
- For SCP and SDWP: Measure the cooling capacity and freshwater production rate of the ADR machine under various operating conditions. Calculate SCP and SDWP based on the measured data and compare them against the specified targets.

[3] Data Analysis and Validation:

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- Analyze Data: Analyze the collected data to evaluate the Adsorption machine's performance against the defined validation criteria for each KPI. Use statistical methods and modeling techniques to assess accuracy and reliability.
- Comparison: Compare measured values with specified limits or targets to determine compliance. Identify any discrepancies or deviations that may indicate performance issues or areas for improvement.
- Iterate and Optimize: Iterate on the validation procedure as necessary to address any discrepancies or optimize performance monitoring. Adjust operating parameters, measurement techniques, or testing protocols as needed to improve accuracy and reliability.

[4] Documentation and Reporting:

- Document Procedure: Document the validation procedure, including test setup, measurement techniques, and results. Maintain detailed records of all data collected during the validation process.
- Prepare Report: Prepare a validation report summarizing the findings, including comparisons of measured values to specified criteria, any deviations from targets, and recommendations for improvement. Provide clear and concise explanations of the validation methodology and results.

[5] Iterate and Improve:

- Continuous Improvement: Continuously refine the validation strategy based on feedback, new insights, and evolving system requirements. Incorporate lessons learned from validation tests to enhance the performance monitoring process and ensure ongoing compliance with KPIs.

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6 Isobaric Expansion Engine

6.1 Technology presentation

Isobaric expansion engines (IEE) are machines operating under constant pressure conditions during the expansion phase, extracting work from an isobaric gas expansion within a cylinder. The most familiar example is the expansion stroke in reciprocating piston engines, where the piston moves within the cylinder while intake or exhaust valves are open, maintaining constant pressure. Traditional types include Worthington and Bush engines, while modern distinctions focus on direct-acting steam pumps and thermo-compressors, distinct from engines like Stirling or Ericson due to lacking polytropic expansion. Isobaric expansion engines continuously expand and compress a working fluid, chosen for their high thermal expansion at high temperatures and low compressibility at low temperatures. They excel as vapor-driven pumps and compressors for their simplicity and efficiency, directly converting heat to pumping and compression without intermediate energy conversions. Energy from pumped liquid flows can be converted to shaft power or electricity using hydraulic motors, or through pump as turbine technology. Direct-acting pumps, or reciprocating pumps, are characterized by a simple configuration, with reciprocating motion of the piston unit driving pumping and suction of liquid in the cylinder. These pumps can operate at high temperatures, handle a wide range of viscosities, and compress gases. The discharge pressure of the liquid can be adjusted relative to the steam pressure based on piston diameters. Traditional configurations include non-regenerative Worthington-type engines, while regenerative versions utilize a regenerator. Thermo-compressors differ by using high-pressure vapor to compress a low-pressure vapor, contrasting with direct-acting pumps that exploit mechanical work.

According to the scheme presented in Figure 1-1, the machine, which is characterized for being a heat source/sink, is composed by three modules: the IEE module, the hydraulic motor module, and the fuel injection system module. The heater (evaporator) receives the waste heat input from the medium-level temperature line at about 90 °C, while the condenser, intended as the cooling element, is connected to the low-level temperature line at about 20 °C. The main specifications of the isobaric engine used in the test are shown in Table 6-1.

Table 6-1: IE Technical specifications

IE Specification			
Unit	Inlet Water Temperature [°C]	Outlet Water Temperature [°C]	Thermal Power [kW]
Heating (source)	90	84	25-30
Cooling (sink)	20	26	20-25
IE Mechanical Integration			

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Presence of hydraulic modules	Yes
Number of Hydraulic modules (critical)	2
IE Electrical Integration	
Power Supply [kWe]	0.1 (max)
Presence of inverter	No

6.2 KPIs

The Validation Campaign Strategy for Isobaric Engine starts from the definition of the KPIs necessary to monito the performance of the machine, dedicated to mechanical work production in the vessel.

Thermal Efficiency

Thermal efficiency is the measure of the useful work output with respect to the heat input. It is a parameter that describes how well the machine converts the heat energy supplied by the source into mechanical work. The formula of thermal efficiency is the following:

$$\eta_{th} = \frac{W_{out}}{Q_{in}}$$

Where W_{out} is the final mechanical work produced by the engine, and Q_{in} the energy input, so the energy required to heat the displaced working fluid from the regenerator outlet to the high cycle temperature.

For Worthington Type machine, the produced work is the difference between the raw pumping work output W_{dc} [J] from the driving cylinder and the work provided to pump the working fluid W_{fp} [J] to the IEE, as described:

$$W_{out} = W_{dc} - W_{fp} .$$

The raw work output of the driving cylinder can be theoretically estimated with the equation:

$$W_{dc} = (p_{high} - p_{low}) * \Delta V_{dc}$$

where P_{high} and P_{low} [bar] are the high- and low-pressure levels at the beginning and end of the expansion process, respectively, and ΔV_{dc} [m^3] the change in steam volume in the driving cylinder. The pumping work, instead, is calculated with equation:

$$W_{fp} = m_{fp} * \Delta h$$

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Where m_{fp} [kg] is the mass of working fluid into the pumped cycle Δh [kJ/kg] is the enthalpy difference at the pump inlet and outlet, depending on the pressure and temperature conditions.

For the Bush Type Engine, the concept of the work output is slightly different. The relation is:

$$W_{out} = \oint pdV_{tot}$$

Where V_{tot} consists of the volumes of the hot space, V_H, the cold space, V_C and the regenerator V_R which does not change during engine operation.

6.3 Validation Campaign Strategy

Regarding the Isobaric Engine technology, the approach is the same as the previous systems. The parameters need instruments able to monitor their performance. Here is the list of equipment:

Oil flow meter and differential pressure sensors

Within the first phase of the validation campaign, the isobaric engine mechanical work output will be assessed by means of the calculation of the work transmitted to hydraulic oil pumped to pressures at around 100 bar. The oil flow rate as well as the throttling of this fluid in between the high and low pressure will serve for estimating the mechanical work achieved by the isobaric engine technology.

Dynamometers

On the second phase of the validation campaign, the isobaric engine prototype will be connected to a hydraulic oil motor for the generation of shaft power. For the assessment of the work output under this configuration, a dynamometer-based system connected to a mechanical brake will be considered. Both the speed and generated torque will be measured from which the mechanical work will be estimated.

Energy Meters

An energy meter will be considered within the activities to be performed at Tecnalia's laboratory validation campaign for the measurement of the electrical energy consumption of the isobaric engine prototype.

Thermocouples or Thermistors

Thermocouples and thermistors are necessary to measure the temperature of the working fluid at the inlet and outlet of the isobaric expansion engine. The monitoring of temperature is fundamental for the correct machine's operation, which aims to minimize losses and optimize mechanical work output.

The analysis of the **primary energy savings** for IEE addresses the calculation of the reduction in fuel injection energy consumption when replacing pumping work generated by the isobaric engine by means of available waste heat from the vessel's propulsion and auxiliary engines. The expected percentage of

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savings is about 1-3% from the baseline. The key steps for the calculation of primary energy savings regarding IEE against the baseline are the following:

- Determine the capacity of the Isobaric Expansion Engine, typically measured in kilowatts (kW) or megawatts (MW), which indicates its ability to generate power or provide mechanical work.
- Multiply the Isobaric Expansion Engine's capacity by the number of hours it operates annually to determine the total energy saved, expressed in kilowatt-hours (kWh) or megawatt-hours (MWh) per year. This provides a measure of the energy efficiency of the Isobaric Expansion Engine compared to traditional heat engines, if similar operating conditions can be gathered with these technologies.
- Asses the mechanical work generated per unit of recovered heat (at medium-low temperature level), determining the primary energy savings by subtracting the Isobaric Expansion Engine's output from the main and/or auxiliary engines fuel injection system consumption (or any other representative on-board mechanical work consumption).
- Estimate the annual energy savings facilitated by the Isobaric Expansion Engine within the energy assessment analysis (transposition of lab scale results to real size vessels).

This chapter encompasses the **Validation Strategy** for IE, listing the key steps for the KPIs calculation:

[1] Define Validation Criteria:

- Thermal Efficiency: Achieve a minimum thermal efficiency value as determined by theoretical calculations or simulations, typically based on the ratio of useful work output to the total heat input.

[2] Validation Procedure:

- For Thermal Efficiency: Operate the isobaric expansion engine under various operating conditions (temperature, pressure, flow rates) while measuring heat input and work output. Calculate the thermal efficiency based on the measured data and compare it against the specified minimum value.

[3] Data Analysis and Validation:

- Analyze Data: Analyze the collected data to evaluate the isobaric expansion engine's performance against the defined validation criterion for thermal efficiency. Use statistical methods and modeling techniques to assess accuracy and reliability.
- Comparison: Compare the measured thermal efficiency with the specified minimum value to determine compliance. Identify any discrepancies or deviations that may indicate performance issues or areas for improvement.

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- Iterate and Optimize: Iterate on the validation procedure as necessary to address any discrepancies or optimize performance monitoring. Adjust operating parameters, measurement techniques, or testing protocols as needed to improve accuracy and reliability.

[4] Documentation and Reporting:

- Document Procedure: Document the validation procedure, including test setup, measurement techniques, and results. Maintain detailed records of all data collected during the validation process.
- Prepare Report: Prepare a validation report summarizing the findings, including comparisons of measured thermal efficiency to the specified criterion, any deviations from targets, and recommendations for improvement. Provide clear and concise explanations of the validation methodology and results.

[5] Iterate and Improve:

- Continuous Improvement: Continuously refine the validation strategy based on feedback, new insights, and evolving system requirements. Incorporate lessons learned from validation tests to enhance the performance monitoring process and ensure ongoing compliance with the thermal efficiency criterion.

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7 Testing Scenarios

This Chapter encompasses the different configurations of the WHR technologies previously described, aiming to replicate the operational conditions respectively for cargo, ferry and cruise vessel at laboratory scale. The integration of many technologies implies a defined strategy for the testing scenarios in order to set a correct operations scheduling, also compatible with the laboratory constraints.

7.1 Technologies Operative Conditions

ORC-HP

The testing scenarios for the ORC validation campaign require different machine settings and many different working conditions.

The analyzed system is a trigenerative WHR ORC-HP technology, which is able to produce electricity but also heating as hybrid system. The purpose is to explore all the possible configurations, analyzing the two different settings:

- Electricity generation only;
- Electricity generation and heating combined.

For each ORC configuration, many operational conditions are suitable for testing, otherwise there are some constraints.

The summary of ORC Operating conditions is provided here:

- Heat supply Temperature: 130-140°C;
- Cooling Supply Temperature: 35°C;
- Chilled Water Supply Temperature: 15°C;
- Power Generation Capacity: 11 kWe;
- Cooling Capacity: 3 kWth.

According to the temperature profile of the machine room, as shown in Figure 1-1, the evaporator exploits the high-temperature level line, which is characterized by approximately 140°C waste heat. The condenser and the subcooling heat exchanger are connected to the low-temperature level line, which register a value of about 20°C.

TES

The testing phase designed for TES system aims to cover all the possible conditions replicable at laboratory scale.

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The TES system that will be tested in the Tecnalia laboratory has a total mass of 645 kg. The pillow plates, the tank and lid and the other main components are made of stainless steel 1.4301. The properties of the HTF and the PCM are presented in Table 7-1 and Table 7-2, respectively.

Table 7-1: HTF properties

Water property	Symbol	Value	Unit
Charge temperature	$T_{f,cha}$	90.0	°C
Discharge temperature	$T_{f,dis}$	70.0	°C
Average density	ρ_f	971.84	kg/m^3
Av. therm. Conduct.	k_f	0.66705	W/m/K
Average dynamic viscosity	μ_f	0.0003541	sPa
Total mass flow rate	m	0.10 – 1.20	kg/s

Table 7-2: PCM properties

PCM property	Symbol	Value	Unit
Initial charge temperature	T_{cha}	70	°C
Initial discharge temperature	T_{dis}	90	°C
Reference melting temperature	T_m	80	°C
Solid state density	ρ_s	900	kg/m^3
Liquid state density	ρ_l	800	kg/m^3
Solid state specific heat	c_s	2.00	kJ/kg/K
Liquid state specific heat	c_l	2.00	kJ/kg/K
Specific fusion latent heat	F	220	kJ/kg
Solid state thermal conductivity	k_s	0.20	W/m/K
Liquid state thermal conductivity	k_l	0.20	W/m/K

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The objective for ZHENIT lab concept is to elaborate the PCM storage emulating the preparation of DHW. As already presented by the tables above, the PCM will be characterized by a reference melting temperature of 80 °C. TES system operating conditions impose an average thermal power of 3 kW and a thermal energy of around 25 kWh. Regarding the phases of TES system, the charging process, which exploits the waste heat at 140 °C, is characterized by the inlet water temperature at 90°C, while the output water temperature is estimated at 70°C. The discharging process comprehends the use of the heat delivered to the cooling water ring or it implies the presence of a DHW tank. The outlet water temperature is 70°C also in this case.

In Table 7-3, the geometric specifications of the main features of the TES system are presented.

Table 7-3: TES configurations

Parameter	Value	Unit
Overall length	1.204	m
Overall height	1.223	m
Overall width	0.664	m
Plate length	1.000	m
Plate height	0.800	m
Plate bundle width	0.460	m
Plate number	10	-
TES mass	645	kg
PCM mass	344	kg
Footprint	0.80	m^2
Energy storage capacity	24.87	kWh
Energy storage density	45.03	kWh/m^3

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The testing conditions for TES system imply two days of experiment: one for charging phase and another one for discharging phase. Indeed, breaking down the testing into separate days for charging and discharging allows for accommodating the respective time requirements of each process. Charging typically involves specific preparation, such as heating or cooling, and may require a longer duration compared to discharging. Similarly, discharging may involve controlled release or utilization of stored energy, which also needs dedicated time for accurate assessment. By allocating separate days, it ensures sufficient time for each phase, optimizing the testing process and results.

AM

The adsorption machine is a module capable of producing cooling or desalinated water, also in hybrid mode. This technology is connected to a wide system of valves, which adjust mass flows and pressures in input, and to a chilled water module, which regulates the chilled water production. Introducing the adsorption machine operating conditions, the heat supply temperature is 90°C, while the cooling supply temperature is about 20-25°C. The chilled water supply temperature is 15°C. The capacity of the machine is 10 kWth. In particular, desalination capacity is in the range of 200-500 liters per day, depending on whether it is operated as a pure desalination maker or simultaneously desalination maker and chiller.

The machine room connects AM to low temperature and medium temperature line the system. The salted water module and the chilled water module are integrated into the machine exploiting the low temperature line. The demand and the waste heat availability are different vessel by vessel, changing in relation to the presence of e-Sail. Power and temperature conditions depend on the ship profile, meaning that many operating fields will be investigated.

IE

The Isobaric Engine is a simple machine able to produce mechanical work. The operating conditions consist of connecting the module to the heat supply line, which is affected by a temperature of 90°C. The cooling supply temperature, instead, is 20°C. The maximum thermal power is around 25-30 kWth, while the mechanical output is expected to be registered at 1 kW. The analysis aims to test all the possible working conditions, which are constituted only by the production of mechanical work under different vessel boundaries. Indeed, the cargo, the ferry and the cruise temperature and demand conditions will be emulated at laboratory scale to test the performance of IE.

7.2 Tests set-up

The testing campaign is conducted at laboratory scale, implying specific boundaries for the vessel's operational conditions. The testing conditions need to be explored by setting up different ranges of temperature at which replicate the vessel conditions and testing the machines. The temperature profile of a vessel has specific conditions that are not subjected to consistent changes during sailing. However, the waste heat availability is very sensible to the dynamic behavior of a vessel. Cargo, Ferry and Cruise vessels have different functions and so different energy demands. Sailing for freight transportation

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rather than people transportation implies very different operating schemes which affect the heat needed by the ship. The objective of the testing campaign is to represent a variety of vessel operating conditions, beginning with the standard temperature profile that remains consistent across different vessels and simulating various levels of waste heat (WH) energy availability. According to the laboratory scheme shown in Figure 1-1, different temperature levels will be emulated in the three rings, categorized as low, mid, and high temperature rings. The temperatures required for the laboratory tests are shown in the next table.

Table 7-4: Explorable Temperature Ranges in laboratory

Testing Temperatures in Lab						
LT Ring			MT Ring		HT Ring	
T1 [°C]	T2 [°C]	T3 [°C]	T1 [°C]	T2 [°C]	T1 [°C]	T2 [°C]
20	30	40	80	90	130	140

The organization of the testing campaign aims to replicate the operational conditions for cargo, ferry and cruise vessels, covering a wide range of explorable conditions in the shipping framework. For each vessel typology, the tests are planned according to the applications required on-board, which are mainly cooling, heating, desalination, electricity generation and mechanical work production. Each mode is affected by a demand, which varies depending on the vessel typology. For each application, a specific WHR system is required, characterized by a specific working profile. The TES system is set for energy storage, and it is composed of two phases: charging and discharging phase. In this case, the TES system is designed for internal supply, specifically for satisfying the domestic hot water demand of the vessel. The TES system applies a power capacity of 40 kW. The test’s duration is an approximate purpose, due to the variable working constraints during the testing day. The duration needed for the circuit’s preheating is about 1-1.5 hours, while the shutting phase is estimated to count for 1 hour. Depending on the technology and its constraints, the testing phase time should vary in a range between 6 to 10 hours per machine. An example of testing day for one system is here provided:

- Preheating phase: from 7.30 am to 9.00 am;
- Testing phase: from 9.00 am to 4.00 pm;
- Shutting phase: from 4.00 pm to 5.00 pm.

The test planning is described in the following tables. In particular, Table 7-5 contains the information about cargo vessel replication tests, Table 7-6 is relative to ferry vessel conditions, while Table 7-7 regards cruise conditions.

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Table 7-5: Testing scenarios for Cargo Vessel

Test	Vessel	Operational Conditions				Duration [h]
		Application	Demand [kW]	Technology	Available Power [kW]	
1	Cargo	Cooling	950	AM	10	1
2		Heating	450	ORC-HP	3	1
3		Desalination	300	AM	10	1
4		Electricity Generation	2,400	ORC-HP	11	1
5		Mechanical Work	250	IE	1	1
6		Domestic Hot Water	300	TES	40	1

Table 7-6: Testing scenarios for Ferry Vessel

Test	Vessel	Operational Conditions				Duration [h]
		Application	Demand [kW]	Technology	Available Power [kW]	
1	Ferry	Cooling	450	AM	10	1
2		Heating	200	ORC-HP	3	1
3		Desalination	150	AM	10	1
4		Electricity Generation	1,200	ORC-HP	11	1
5		Mechanical Work	150	IE	1	1
6		Domestic Hot Water	400	TES	40	1

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Table 7-7: Testing scenarios for Cruise Vessel

Test	Vessel	Operational Conditions				Duration [h]
		Application	Demand [kW]	Technology	Available Power [kW]	
1	Cruise	Cooling	1,600	AM	10	1
2		Heating	550	ORC-HP	3	1
3		Desalination	600	AM	10	1
4		Electricity Generation	4,000	ORC-HP	11	1
5		Mechanical Work	400	IE	1	1
6		Domestic Hot Water	700	TES	40	1

The testing scenarios provide a practical plan to understand the behavior of the different machines under various operational conditions for the three vessels. After the data collection, results could be elaborated in order to evaluate the presence of e-Sail. This element modifies the propulsion settings and, under favorable wind conditions, contributes to relevant energy savings but it reduces the waste heat available on-board. The data analysis should follow a theoretical investigation of the e-Sail influence for different types of vessels and navigation profiles, and its impact on the waste heat availability. Moreover, it is important to consider the different waste heat profile characterizing each vessel. The dynamic behavior of a vessel is specific and varies depending on many factors. The data analysis should cover many possible waste-heat availability conditions, with respect to the presence of e-Sail, which influences the maximum waste-heat available. As a reference, the maximum low, mid, high waste-heat capacities are summarized in Table 7-8, according to different savings conditions achieved with the eSail technology for the different investigated vessels.

Table 7-8: Data Analysis for e-Sail

Vessel	eSail Propulsion savings	WH Available [kW]		
		LT	MT	HT
Cargo	0%	6,600	6,600	19,800
	10%	5,940	5,940	17,820
	20%	5,280	5,280	15,840
Ferry	0%	2,700	2,700	7,290
	10%	2,430	2,430	6,561

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Vessel	eSail Propulsion savings	WH Available [kW]		
		LT	MT	HT
	20%	2,160	2,160	5,832
Cruise	0%	10,400	10,400	31,200
	10%	9,360	9,360	28,080
	20%	8,320	8,320	24,960

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8 Conclusions

The objective of this document is to define the most prominent KPIs for the WHR technologies regarding ZHENIT project and create a validation campaign strategy based replicable at laboratory scale, concerning different types of vessels, which are affected by different boundary conditions.

The KPIs are chosen based on the performance of the machines and their output. The testing scenarios have the goal to describe the trend of those parameters and infer results in favor of replication on-board. Each KPI is measured through a proper series of instruments which constitute the necessary list of equipment. The validation of the obtained results is reached through mathematical modelling and the application of statistical methods.

The testing site is the Tecnalia's laboratory, which is characterized by precise working conditions suited to replicate the real operating conditions of Cargo Vessel, Ferry Vessel, and Cruise Vessel, according to the possible different applications of the waste heat on-board. In particular, the amount of waste heat is influenced by several factors including the presence of e-Sail, which is a relevant discriminant for the data analysis.

The testing scenarios have been proposed exploring all the possible configurations available from the WHR technologies integration considering different types of vessels and required operating modes (demands). The waste heat line has been divided into three different temperature levels, which characterizes the input and the output for the chosen scenarios. The number and duration of the tests to be performed are thereby defined according to the different testing scenarios while taking into consideration both the laboratory and pilot vessel operational characteristics.

This document represents a guideline to be followed in the planning activity of the laboratory and for the pilot vessel, creating a precise list of equipment needed, parameters to monitor and steps to perform on the stage. The trend of many results should be not only the final goal of this work but the also the starting point for the interpretation of the results, aiming to deeply understand the behavior of the technologies involved in ZHENIT project under different working conditions.

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[1] Sabino J. Chapero, ZHENIT, *D 1.2 - Hybrid propulsion on-board integration and guidelines for coupling it with WHR solutions*, July 2023.

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Annex A

Pilot Vessel Specifications

D1.0 ZHENIT Test Specifications

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

D 4.1 | KPI Definition and overall ZHENIT validation campaign strategy

Version 0.4| February 2024

HORIZON-CL5-2021-D5-01-10

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

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Document History

Project Acronym	ZHENIT
Project Title	ZHENIT - Zero waste Heat vessel towards relevant Energy savings also thanks to IT technologies
Project coordination	RINA-C
Project duration	42 month – from 1/06/2022 to 30/11/2025
Title	D 4.1 - KPI Definition and overall ZHENIT validation campaign strategy
Dissemination Level	Confidential
Status	-
Version	0.4
Work Package	-
Lead Beneficiary	-
Other Beneficiaries	-
Author(s)	Francesca DI GRUTTOLA, Giorgio BONVICINI
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Date	Ver.	Contributers	Comment
29/02/2024	0.1	Francesca DI GRUTTOLA and Giorgio BONVICINI (RINA-C)	First writing draft
07/03/2024	0.2	Andrea FRAZZICA	Final Review
07/03/2024	0.3	Alessandro MACCARI	Final Review

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List of Organizations

Participant Name		Short Name	Country	Logo
1	RINA Consulting Spa	RINA-C	Italy	
1.1	RINA Services Spa	RINA-S	Italy	
2	Ethnicon metsovion polytechnion	NTUA	Greece	
3	Danelec	KYMA	Norway	
4	Fundacion tecnalia research & innovation	TECNALIA	Spain	
4.1	Universidad del pais vasco/ euskal herriko unibertsitatea	UPV/EHU	Spain	
5	Anonimi naftiliaki eteria kritis (anek) s.a.	ANEK	Greece	
6	Consiglio nazionale delle ricerche	CNR	Italy	
6.1	Consorzio di ricerca per l'innovazione tecnologica, sicilia trasporti navali, commerciali e da diporto scarl	NAVTEC	Italy	
7	Sorption technologies gmbh	SORTECH	Germany	
7.1	Sorption technologies srl	SORTIT	Italy	
8	Bound 4 blue sl	B4B	Spain	
9	Encontech bv	ECT	Netherlands	
10	Gruppo SIGLA srl	SIGLA	Italy	
11	The university of Birmingham	UoB	United kingdom	

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Table of Content

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List of Figures

No table of figures entries found.

List of Tables

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Abbreviation and Acronyms

Acronym	Description
WH	Waste Heat

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Executive Summary

The Consortium is evaluating the possibility of using another vessel, in place of La Naumon, for the demonstration campaign on board. In fact, in the pathway to prove the 20% of energy savings onboard, it turned out that La Naumon, chosen in the proposal phase, currantly has obsolescent wing sails and has no class certification. This situation can jeopardize the objectives of the overall project, especially the evaluation of the different dynamic effects resulting from the interaction between the vessel propulsion systems, the e-SAIL and the Zhenit solutions onboard, i.e., sorption desalination and cooling system.

The present document defines the test methodology and its draft timeline, to be shared with Fincantieri and evaluate the possibility of using an alternative demo vessel for the tests on board, during navigation and/or at quayside, to achieve Zhenit's objectives.

According to the Grant Agreement, the specific objective related to the demonstration campaign is to "*Validate on-board of La Naumon a WH-to-Cooling/Desalination prototype valorising exhaust engines WH and optimizing its management in coordination with wingsail*". The target to be reached is at least 250 hours of operation. However, the wingsail will be tested on another vessel, therefore 250 hours should be considered cumulative between the two types of tests.

Zhenit - Waste Heat-to-Cooling/Desalination Prototype Test Specification

The main engine High-Temperature (HT) cooling water system - also known as jacket cooling water (JCW) – is normally used for cooling the cylinder liners, cylinder covers and exhaust gas valves of the main engine and heating of the fuel oil drain pipes. However, it can be assumed that a thermostatically controlled regulating valve is located at the inlet to the jacket water cooler, or alternatively at the outlet from the cooler. The regulating valve keeps the main engine cooling water outlet at an almost fixed temperature level, independent of the engine load. The controller for the thermostatically controlled regulating valve must be able to receive a remote variable set point from the main Engine Control System (ECS). it is recommended to keep the engine preheated, to prevent temperature variation in the engine structure and corresponding variation in thermal expansions and possible leakages. For the tests, the jacket cooling water outlet temperature should be kept as high as possible and, in general, should be increased to at least 50°C before starting up the engine. The preheating system available oj board is to be verified (e.g. a built-in preheater in the jacket cooling water system or using cooling water from any auxiliary engine, or a combination of the two). Normally, a minimum engine jacket water temperature of 50°C is recommended before starting the engine. Then the engine should be run up gradually to 80% and 90% SMCR speed (SMCR = specified maximum continuous rating, expressed in

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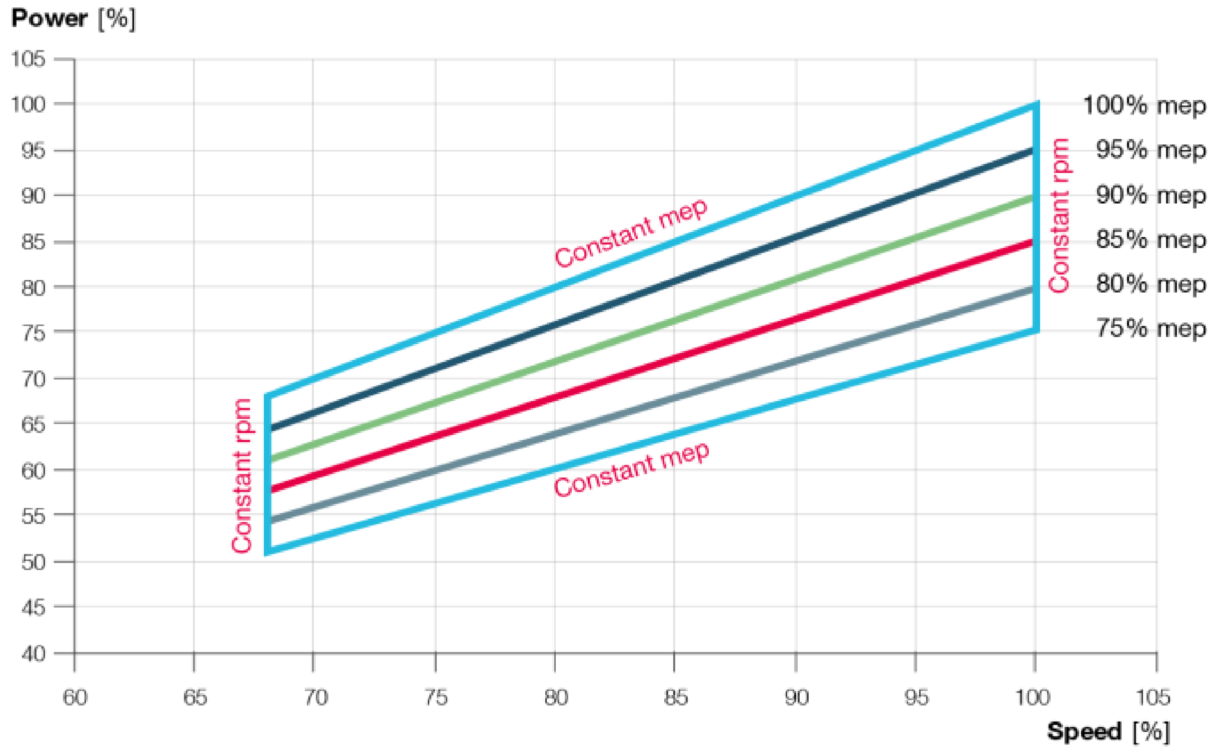
rpm), e.g. during 30 minutes. For running up between 90% and 100% SMCR rpm, it is recommended that the speed be increased slowly over a period of 60 minutes. In case it is not possible to comply with the above-mentioned recommendation, a minimum of 20°C could be considered before the engine is started and run up slowly to 80% SMCR rpm. Before exceeding 80% SMCR rpm, a minimum jacket water temperature of 50°C should be obtained before the above described normal start load-up procedure may be continued.

The following figure is only indicative of an engine load diagram. Within the layout area, there is complete freedom to select the engine's specified SMCR which best suits the demand for power and speed of the ship



The Tests on Waste Heat-to-Cooling/Desalination Prototype are expected to be carried out for at least 4-5 days to fulfil the desired outcomes, corresponding to a mix of different engine load condition (e.g. 65-80-90-100% load) to measure the corresponding JCW temperature - in any case lower than 100°C or as specified by the engine manufacturer.

As already mentioned, the temperature variations are directly depending on the regulation of the thermostatic valve which keeps the main engine cooling water outlet at an almost fixed temperature level, independent of the engine load, regulating the jacket cooling water flowrate. The temperatures may be influenced by the ambient temperature conditions.

The introduction and integration of the Waste Heat-to-Cooling/Desalination Prototype in the JCW system should be carefully verified in advance, to prevent any negative effect on the engine and its

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auxiliaries (e.g. size of the expansion tank and de-aerating tank, venting piping and valves, automation setpoints, etc.).

All the phases of the tests - verification, ispection, startup and shutdown, set-up of monitoring procedures, etc. - will be considered as a part of the target hours (i.e., 250 hours), but excluded by the operating days (4-5 days), which are in principle destined to the testing of WH-to-Cooling/Desalination technology only.

In preparation of the tests, the main parameters to be monitored on board during the test are:

- The engine load and the corresponding water temperature in the JCW system, to be acquired from the vessel automation system, corresponding to different conditions that can occur during the navigation, always in compliance with the manufacturer recommendations for the engine operations.
- JCW flowrate and temperature at the inlet of the sorption unit, to remain within the specified range for the refrigeration / desalination process;
- Temperature at the outlet of the sorption unit to quantify the temperature drop and the consequent effectiveness of that heat source;
- Electrical consumption of the sorption unit and of the related auxiliary systems, to be used in the energy efficiency calculation;
- Chilled water flowrate and temperature at the inlet and at the outlet of the sorption unit to calculate the cooling capacity of the unit;
- Electrical consumption of the desalination unit to assess the complete energy efficiency of the desalination process;
- Flowrate and salinity of seawater at the inlet of the desalination unit and salinity of freshwater at the outlet of the desalination unit to verify the performance of the equipment.

The overall timeline for the demostration campaign is reported in the following Table 9:

Table 9: Timeline of the main tasks

Tasks and Milestones	Deadline
Engineering and Commissioning in the demo vessel	*November 2025*
- Prototypes design completed for each innovative ZHENIT technology	November 2023

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- Technologies manufactured, commissioned and approved at the factory, ready for shipping to the demo vessel	September 2024
- Zhenit technologies shipped to the demo vessel. Start of installation on board and of integration of control & monitoring equipment.	November 2024
- Finalization of the commissioning of the energy management systems and relevant control equipment on-board. All ready to start the test campaign	March 2025
- Start of the test campaign	March 2025
- Issue of the final report of the test campaign	November 2025

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