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

ZHENIT Solutions | Scale-up and replication feasibility studies

WP5 – Technologies evaluation and impact assessment towards replication

Version 1.0 / May 2026

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	47 months – from 1/06/2022 to 30/04/2026
Title	ZHENIT Solutions Scale-up and replication feasibility studies
Dissemination Level	Sensitive
Status	Final version for submission
Version	1.0
Work Package	WP5
Lead Beneficiary	RINA-C
Other Beneficiaries	ECT, ATTICA, NAVTEC, SORTECH
Author(s)	RINA-C
Reviewers	B4B, CNR, SORTECH

Date	Ver.	Contributors	Comment
31/03/2026	0.1	Stefano Bovicelli, Alberto Marasi (RINA-C)	Writing – Original Draft & Review
21/04/2026	0.2	Sabino José Chapero Baranda (B4B)	Technical review
23/04/2026	0.3	Walter Mittelbach (SORTECH) Andrea Frazzica (CNR)	Technical review
08/05/2026	0.4	Stefano Bovicelli, Alberto Marasi (RINA-C)	Review implementation
14/05/2026	1.0	Fiorella Valenti (RINA-C)	Document ready for submission

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Abbreviation and Acronyms

Acronym	Description
AE	Auxiliary Engine
BHP	Braking Horsepower
COP	Coefficient of Performance
DEFRA	Department for Environment, Food and Rural Affairs
GHG	Green House Gases
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
HVAC	Heating, Ventilation & Air Conditioning
IEE	Isobaric Expansion Engine
IMO	International Maritime Organization
LHV	Low Heating Value
ME	Main Engine
MED	Multi-Effect Desalination
MGO	Marine Gas Oil
MMSI	Maritime Mobile Service Identity
ORC	Organic Rankin Cycle
PBT	Pay Back Time
PCM	Phase Change Material
ROM	Rough Order of Magnitude
Ro-Ro-Pax	Roll-on/Roll-off Passenger
RPM	Rotation Per Minute
SFC	Specific Fuel Consumption
SR&D	Sorption Refrigeration and Desalination
SWRO	Seawater Reverse Osmosis

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Acronym	Description
TES	Thermal Energy 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 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 potential, and efficiencies. The primary technologies under scrutiny in the ZHENIT project encompass Organic Rankine Cycles (ORC), Thermal Energy Storage (TES), Sorption Desalination & Refrigeration and Isobaric Expansion Engines (IEE).

The present document constitutes the Deliverable D5.3 focused on “Scale-up and replication feasibility studies” and it is produced within Task 5.1, “How to replicate ZHENIT Solutions in different vessels (size, purpose etc.) towards at least 20% savings”. This document aims at evaluating the replication potential of the four technologies included in the project, scaled up for different vessels application. Specifically, the report assesses techno-economic feasibility study of the proposed technologies implemented on a fishery, on a cargo and on a cruise vessel.

This document, starting from the analysis of operational conditions of each vessel, evaluates energy, fuel and GHG savings with respect to a given baseline, considering the project objective of reaching 20% savings, the main architectural constraints to face on-board, and simple economic parameters to estimate economic performance. The deliverable shows that results are highly affected by vessel operational conditions, presenting peculiarities that can either lower or enhance the attractiveness for real world implementations.

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1 Introduction

This deliverable is titled "Scale-up and replication feasibility studies" and constitutes ZHENIT project deliverable D5.3, prepared within the framework of Work Package (WP) 5 and delivered at M47.

The aim of this task is to elaborate a feasibility study of each WHR technology developed within ZHENIT project, namely Organic Rankine Cycles (ORC), Thermal Energy Storage (TES), Sorption Desalination & Refrigeration and Isobaric Expansion Engines (IEE), implemented on three different vessel typologies, constituted by a fishing, a cargo and a cruise vessel.

A feasibility study is an analysis assessing technical, operational and economic feasibility of a given solution within defined conditions. This includes the identification of system requirements, boundary conditions, integration constraints, comparing scale-up scenarios with expected results. The study should provide a structured evaluation of the replicability potential of each system, reflecting the effectiveness of real-world implementation. In this case, feasibility focuses on the integration of WHR technologies on-board vessels, considering real operation profiles and energy demands. The energy saving has been selected as the comparative term to quantify the effectiveness of each solution, which target has been set to 20% with respect to business-as-usual scenario.

The scale-up is performed by evaluating the transition from laboratory to on-board implementation, analyzing how system performance, energy recovery potential and integration complexity evolve while increasing or reducing size and facing operational variability.

Conducting a feasibility study enables the technical operators to gain an overview of the potential for replication across different vessel categories and specific operational scenarios. This allows stakeholders to understand the benefits and limitations of deployment across vessels with different characteristics.

The main parameters under evaluation are:

- Saving assessment, including the energy and fuel saved annually, as well as the avoided GHG emissions;
- Architecture constraints, including the main on-board infrastructural conditions to consider;
- Economic assessment, including the estimation of simple economic indicators to assess financial feasibility.

In the ZHENIT framework, it is fundamental to highlight the differences between each context on which a certain technology is applied, since each vessel is characterized by specific design features, operational profiles, energy demand patterns and available waste heat source.

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The present report is structured as follows:

- Chapter 1: Introduction;
- Chapter 2: Assumptions and limitations;
- Chapter 3: Vessels description;
- Chapter 4: Organic Rankine Cycle analysis;
- Chapter 5: Adsorption Machine analysis;
- Chapter 6: Isobaric Expansion Engine analysis;
- Chapter 7: Thermal Energy Storage analysis;
- Chapter 8: Replicability potential evaluation; and
- Chapter 9: Conclusions and recommendations.

Starting from Chapter 4, each section first provides a description of the technology involved in the analysis, followed by the scale-up and feasibility study. This includes an energy assessment, an evaluation of architectural constraints, and an economic analysis of the WHR technology under consideration. Finally, a replicability matrix is presented for each solution, summarizing the key points highlighted in the relative paragraph.

This work is developed through the review of submitted ZHENIT deliverables. Particularly, the two main works studied are *D1.1 – WHR for Maritime applications catalogue*, and *D5.2 – ZHENIT Solutions SWOT analysis for replication*.

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2 Assumptions and limitations

The present scale-up and replication feasibility study is subject to several assumptions and limitations that should be considered when interpreting obtained results.

- Due to the lack of pilot-scale demonstration data, the scale-up of the technologies studied has been intended as pure theoretical evaluation, with the objective of obtaining reasonable estimations of on-board performance. Consequently, the results should be interpreted as theoretical indications;
- The overall reliability of the assessment is strongly dependent on the accuracy of the input data provided. In cases where input data are affected by simplifications, the quality level of the feasibility study may be correspondingly reduced, highly affecting final outcomes;
- The vessel technical characterization, particularly for engines analysis, is based on preliminary input data and operational hypotheses provided by technical partners concerning navigation routes and mission profile. For instance, the estimation of task durations plays a critical role in the calculations; therefore, these assumptions may significantly affect the results;
- Regarding conversion factors, UK Department for Environment, Food & Rural Affairs (DEFRA)[1] datasheet has been taken as reference. Specifically, density of marine gas oil (11.825 kWh/kg) and GHG emissions factor for marine gas oil (0.274 $kgCO_2e/kWh$) have been considered;
- Assessing waste heat availability on the vessels, literature assumptions have been used. In particular, as reported by Miller et al.[2], on a general reference vessel the waste heat component represented by exhaust gas is around 35% of the total waste heat, while the water jacket is about 25%. Moreover, according to U.S. Department of Transportation, Maritime Administration[3], exhaust gases may account for up to 40% of recoverable waste heat, while jacket water may represent a lower share, around 15%, depending on engine configuration and operating conditions, highlighting that the distribution of waste heat is

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[1] https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2025

[2] Miller, T.; Durlik, I.; Kostecka, E.; Kozlovska, P.; Jakubowski, A.; Łobodzińska, A. Waste Heat Utilization in Marine Energy Systems for Enhanced Efficiency. *Energies* **2024**, *17*, 5653. https://doi.org/10.3390/en17225653

[3] U.S. Department of Transportation, Maritime Administration. Energy Efficiency and Decarbonization Technical Guide. November 2022. Link: https://www.maritime.dot.gov/sites/marad.dot.gov/files/2022-11/Energy%20Efficiency%20%26%20Decarbonization%20Technical%20Guide%20%2810-2022%29.pdf

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not fixed, but varies significantly as a function of engine size, load profile, and vessel category;

- Due to the lack of specific mechanical data for vessels engines, the mechanical efficiency of the engines, which is function of the specific engine load, has been considered a set value;
- Energy savings are calculated by assuming 100% load operation of the implemented technologies. However, this condition is not expected to occur anytime in real world operations. Therefore, the analysis adopts a conservative approach in terms of system compatibility, representing the most energy-consuming operational scenario;
- When assessing energy savings, two scenarios have been defined:
  - Scenario 1: integration of prototype technology;
  - Scenario 2: implementation of optimized configurations based on Scenario 1 outcomes;
- Regarding Scenario 2 analysis, a linear scaling approach has been adopted to interpolate both technical performance and cost parameters across designed size. This assumption has been necessary due to the lack of detailed information on how energy demand/production and capital costs vary as function of technology scale;
- The economic assessment is developed as a simple order-of-magnitude analysis to estimate the economic feasibility of a given technology for a specific scenario. Simple Pay Back Time (PBT), calculated using a basic formulation (PBT = CAPEX / annual savings), has been adopted as indicator, without accounting for OPEX variability or any financial structuring.
- CAPEX values refer to T5.2 data, based on the assumptions provided by partners, and they do not consider vessel integration costs, which could be much higher depending on the specific case;
- The marine gas oil price has been derived from market data referenced to Rotterdam, consistently with World Bunker Prices[4] benchmarks. In particular, the reference value is 675.5 $/Mt, converted into 587.7 €/Mt.

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[4] *World Bunker Prices - Ship & Bunker*

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3 Vessel description

3.1 Fishery

The reference fishing vessel for this assessment is TESEO, a fishery sailing Sicilian seas around Mazara del Vallo. Within the Italian fleet, TESEO is one of the most important vessels for trawling, mainly intended for catching shrimp. The fleet, in the 80s and 90s, reached a number close to 400 units, which has gradually been reduced following the policies of incentive for the sale of licenses by the European community. The number of fishing vessels currently operating is around 80 units.

Figure 3.1: TESEO Fishery

The vessels in the fleet have common characteristics that can be summarized as follows:

- Length around 30 m
- Gross tonnage around 100 t
- Installed power – max 600 kW (propulsion)
- Average age since launch – 40 years
- Average age since refit – 10 years
- Operational mission – 30 days of continuous operations at sea
- Fishing depth – 50 to 500 m depth, trawling technique

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- Water storage lockers – 20 t
- Diesel crates – 10,000 l
- Metal hull

The data collection for Mazara del Vallo fishery has brought several details over a reference journey. The hours for each mission phase have been measured. A typical mission profile over 24 hours consists of:

- Time to deploy (4 times) the entire fishing gear (approximately 2,000 m of steel cables with otter boards, around 200 m of fishing lines, fishing net): 2 hours;
- Trawling activity (4 hauls at depths of approximately 600 m, each lasting 4 hours and 30 minutes): 18 hours;
- Time to retrieve (4 times) the entire fishing gear (approximately 2,000 m of steel cables with otter boards, around 200 m of fishing lines, fishing net): 2-3 hours (most of the time consumption is due to the winch).

This information has been combined with the details of the reference journey to provide a baseline for estimating the energy consumption of the main and two auxiliary engines. The annual task durations have been estimated based on 10 journeys per year.

Table 3.1 shows the duration of each task for the TESEO vessel.

Table 3.1: TESEO task duration

Reference Journey Task	Value per Journey	Value per Year
Total journey duration	30 days	300 days
Total miles	7,000 miles	70,000 miles
Total maneuvering time	280 hours	2,800 hours
Navigation time	390 hours	3,900 hours
In-port operations time	48 hours	480 hours

Regarding the technical specifics of the vessel, there are two types of engines:

- One main engine, model Weichan x6170 W13 – IMO Tier 2 of 367 kW power capacity;
- Two auxiliary engines, model Baudouin 6W105S of 168 kW power capacity .

From an energy perspective, it is necessary to define an average fuel consumption for these phases. As there is no measured data, the vessel's fuel consumption is estimated by using the Specific Fuel Consumption (SFC) parameter.

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Main Engine

For the main engine, Table 3.2 expresses the SFC of MGO at different loads, as reported by fishery datasheets.

Table 3.2: Specific Fuel Consumption of TESEO main engine at different loads

ME Load (%)	Velocity (rpm)	SFC (g/kWh)
100	1200	210
75	900	200
50	600	230
25	400	265

For each vessel task, it is assumed a realistic average load, compatible with the reference task. Consequently, it is possible to estimate the average ME power used in a specific shipping phase, as well as the average ME energy and fuel consumption. The data are presented as follows:

Table 3.3: TESEO navigation phases technical characteristics

Phase	Load (%)	SFC (g/kWh)	ME Power used (kW)	Duration (h/y)	ME Energy Consumption (kWh/y)	ME fuel consumption (t/y)
Navigation	50	230	183.5	3,900	715,650	164.6
Maneuvering	25	265	91.75	2,800	256,900	68.1
In-port operations	0	0	0	480	0	0
Total	-	-	-	-	**972,550**	**232.7**

To estimate the amount of waste heat available from the main engine, it is first necessary to determine the mechanical efficiency. The data collection phase provided the SFC at different engine loads. Since mechanical efficiency varies with the load, an average operating load is assumed to simplify the calculation.

Considering just the operations mentioned in Table 3.3 as the most relevant phases for each journey, the average SFC during sailing is assumed to be the mean value between the SFC measured at 50% and 25% load. The calculated average SFC corresponds to 0.247 kg/kWh.

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Based on this assumption, the mechanical efficiency of the main engine can be estimated by multiplying the average SFC by the lower heating value (LHV) of MGO. This product yields a non-dimensional parameter whose inverse corresponds to the engine's mechanical efficiency under the assumed operating conditions. The resulting value is approximately 34%, meaning that about 66% of the fuel's energy content is released ad waste heat.

To quantify the annual amount of waste heat available on board, this coefficient is applied to the annual energy consumption of the main engine. The annual energy consumption by ME is 972,550 kWh/y and it corresponds to an annual fuel consumption of 232.7 t/y. By applying the waste heat fraction (66%), the total waste heat generated by the main engine is **640,246.0 kWh/y**, which corresponds to **153.2 t/y** of fuel energy not converted into useful mechanical work.

After estimating the total waste heat available, it is necessary to identify the main waste heat sources and their relative contributions. As reported by Miller et al.[5], approximately 35% of the total waste heat is associated with exhaust gases, while around 25% is transferred to the jacket water circuit. Therefore, **224,086.1 kWh/y** of waste heat is under the form of exhaust gas, while **160,061.5 kWh/y** of waste heat comes from jacket water circuit.

Auxiliary Engine

Moving to auxiliary engines consumptions, the collected data is based on declared operational usage and a combination of electrical loads. In fishing vessels, auxiliaries typically have relatively low energy consumption and are mainly used to sustain on-board electrical operations. The gensets supply electricity for the main on-board electrical loads, such as cooling system, desalination, lighting, winch and other fishing machinery. The total gensets electricity output per journey is 65,000 kWh. Therefore, considering 10 journeys per year, the AE annual energy consumption is **650,000 kWh/y**. The Baudouin engine rated SFC is 216 g/kWh. The total annual AE fuel consumption is **140.4 t/y**.

The provided data about gensets productivity imply an unusual scenario in which the total fuel energy required by the auxiliaries approaches or exceeds the ME one. Typically, industrial fishing vessels are characterized by ME fuel consumption dominance due to navigation, while AE demand lower fuel energy consumption. The current Rough Order of Magnitude (ROM) data provided by Navtec suggests either an overestimation of AE energy demand or an underestimation of ME operational loads. Such imbalance may affect the waste heat recovery potential. A deeper assessment of both ME and AE fuel energy consumption, based on measurable parameter, is recommended to ensure realistic energy and WHR estimations. Moreover, since fishing vessels are often saturated of equipment, the potential

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[5] Miller, T.; Durlik, I.; Kostecka, E.; Kozlovska, P.; Jakubowski, A.; Łobodzińska, A. Waste Heat Utilization in Marine Energy Systems for Enhanced Efficiency. *Energies* **2024**, *17*, 5653. https://doi.org/10.3390/en17225653

valorization of the heat available may face relevant installation challenges, requiring detailed analysis of space constraints.

3.2 Cargo

The vessel ANKIE (IMO 9331359, MMSI 244554000) is a General Cargo Ship built in 2007 (19 years old) and currently sailing under the flag of Netherlands.

Figure 3.2: ANKIE Cargo

The vessel mechanic system is equipped with Wärtsilä 9L20 as main engine, characterized by a power capacity of 1,800 kW. It is a 4-stroke, inline 9-cylinder, turbocharged and intercooled diesel engine, and it typically operates at 900 rpm.

The engine can switch over from MDO to HFO and vice versa without power interruption at any engine operation load.[6] This propulsion system observes an average specific fuel consumption of 195 g/kWh. This specific fuel consumption and power rating corresponds to a brake thermal efficiency of roughly 40-42%. The vessel is also equipped with auxiliary engines that provide electrical power for shipboard systems. Each engine typically produces between 400 and 600 kW, supporting hotel loads such as lighting, HVAC, refrigeration, pumps, as well as port operations, such as cargo handling.

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[6] https://www.jadepowerplants.com/site/assets/files/1354/wartsila_20_brochure.pdf

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The first step is to identify the waste heat sources and quantify how much energy is available for recovery. This clarifies the baseline condition to be compared with the project's scenario. On cargo vessel, there are three main sources of waste heat:

- Exhaust Gases of Main Engine: High mass flow, continuous flow, high temperature level ranging between 300-400 °C.
- Exhaust gases of Auxiliary Engines: medium mass flow, useful for secondary operations, medium temperature level ranging between 200-300 °C
- HT cooling water: little mass flow with a temperature range between 80-100 °C.

Main engine

The analysis of Ankie main engine characteristics is based on the weighted mean power for each vessel task, described in the technical documents provided by Attica. Consequently, it is assumed the hours dedicated for each task during the year. It is considered for a medium cargo vessel such as MV Ankie, that operates typically across northern Atlantic European seas, about 40% of annual navigation time is on open sea sailing, meaning approximately 3,500 h/y. Transit in confined and narrow waters is assumed to represent the 20% of this time, equal to 1,750 h/y. Loading and unloading operations are significant tasks for cargos, representing about the 25% of the year, translated into 2,200 h/y, where the main engine remains turned off or has very low consumption. For the remaining time, about 15%, corresponding to 1,300 h/y, the vessel remains in waiting and standby condition, with electric and ventilation systems turned on. In Table 3.4 the mean weighted energy consumption from main engine is presented.

Table 3.4: Ankie main engine task description

Task	ME weighted mean power (kW)	Annual duration (h/y)	ME weighted mean energy (kWh/y)
Open sea transit	610.2	3,500	2,135,700
Confined water transit	423.1	1,750	740,425
Waiting/standby	0.1	1,300	130
Loading/discharging	0.1	2,200	220

The total amount of MV Ankie Wartsila 9L20 main engine energy consumption is **2,876,475 kWh/y**, considering the given assumptions.

Calculating the waste heat available for WHR, it is necessary to estimate the engine's mechanical efficiency, and it is assumed to be 42%, considering main engine specifications. Therefore, 58% of the

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total energy consumption is released as waste heat. However, only a fraction of this heat is recoverable, due to losses in the jacket water system, cooler circuits, and mechanical inefficiencies. The breakdown of waste heat components is variable due to fuel and type and different ME loads during navigation. However, it has been estimated by Miller et al.[7] that approximately 35% of waste heat is represented by exhaust gas component, while 25% by jacket water system. Therefore, the amount of waste heat available from the exhaust gas component is estimated to be around **583,924.4 kWh/y**, while the jacket water component results in **417,088.9 kWh/y**.

Auxiliary engine

The technical documentation shared by Attica included also the auxiliary engine energy profile. Similarly to the main engine analysis, the weighted mean power is calculated for the different vessel operational tasks calculating the weighted mean power for open sea transit, confined water transit, waiting/standby and loading/discharging. The annual operating hours for the tasks are the same as in the previous case. It is fundamental to recognize the operating differences between ME and AE: ME is dedicated principally to propulsion, while AEs are designated to electricity production for many activities on board. Therefore, AE power and so energy consumptions are similar for each different vessel task with respect to the ME case, where the power and so the energy consumptions are mostly directed to open sea transit. The weighted mean power and corresponding annual energy consumption for each operational task are reported in Table 3.5.

Table 3.5: Ankie auxiliary engines technical characteristics

Task	AE weighted mean power (kW)	Annual duration (h/y)	AE weighted mean energy (kWh/y)
Open sea transit	38.9	3,500	136,150
Confined water transit	43.6	1,750	76,300
Waiting/standby	38.9	1,300	50,570
Loading/discharging	32.3	2,200	71,060

The total amount of weighted mean energy consumed by AE is **334,080 kWh/y**. This energy could be used for several electricity-driven activities on-board. To evaluate potential savings associated with the WHR system, it is necessary to estimate the useful electrical output generated by the auxiliary engines.

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[7] Miller, T.; Durlik, I.; Kostecka, E.; Kozlovska, P.; Jakubowski, A.; Łobodzińska, A. Waste Heat Utilization in Marine Energy Systems for Enhanced Efficiency. *Energies* 2024, *17*, 5653. https://doi.org/10.3390/en17225653

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Since the specific efficiency of the AEs is not provided in the available documentation, an efficiency value of 42% is assumed, consistent with the assumption adopted for the main engine.

If the useful work produced by the auxiliary engines is entirely converted into electricity generation, the total amount of electrical energy supplied onboard is estimated to be approximately 140,314 kWh/y.

3.3 Cruise

The reference cruise vessel for this assessment is the Ro-Ro Pax vessel ELYROS (Figure 3.3), which is operated by the Greek company ANEK Lines. Built by Mitsubishi Heavy Industries in Shimonoseki, Japan, in 1998, the vessel was purchased by ANEK Lines in 2007. Following significant renovations, it was put into service in 2008.

Figure 3.3: ELYROS Cruise

The cruise vessel with IMO 9178599 and MMSI 240685000 operates mainly on the route between the Port of Piraeus (Athens) and Chania (Crete), and has the following main characteristics[8]:

- Length: 192m;
- Hull: single steel hull;
- Service Speed: 24 knots;
- Garage: 620 cars;

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[8] https://anekitalia.com/en/ferries/elyros-en/, Accessed 12/03/2026.

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- Number of passengers: 1,874;
- Cabins: 235;
- Airplane-Type seats: 323;
- Services: Internet Wi-Fi, telemedicine, shops, bars, restaurants and self-services and slot-machine area.

The vessel is powered by two Pielstick 12PC4-2 main engines, each consisting of 12 cylinders and delivering 13,092 kW at 400 rpm (for a combined output of 26,184 kW / 35,600 bhp). In addition, the vessel is equipped with four Daihatsu 6DK-26 generator sets, each rated at 1,324 kW at 720 rpm, providing a total auxiliary power output of 5,296 kW.[9]

The main engines can operate on both HFO (Heavy Fuel Oil) and MGO (Marine Gas Oil), whereas the auxiliary engines run exclusively on MGO. When in port, the vessel uses MGO only.

- Based on the latest available operational data (2025), the vessel achieves the following performance in terms of voyage duration (Table 3.6) and fuel consumption (

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[9] https://www.scheepvaartwest.be/CMS/index.php/car-carriers-ro-ro/172-elyros-imo-9178599, Accessed 12/03/2026.

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- Table 3.7):

Table 3.6: Elyros Voyage Duration

Parameter	Value per Year (2025)	Value per Trip (Average)
Voyage Number	314	1
Distance	49,144 nm	157 nm
Total Navigation Time	2,748.8 h	8.8 h
Total Maneuvering Time	99.3 h	0.3 h
Total In-port Time	3,942.7	12,5 h

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Table 3.7: Elyros Fuel Consumption

	Value per Year (2025)	Value per Trip (Average)
HFO Consumption (Prop)	3,358 MT	27.5 MT[10]
MGO Consumption (Prop)	5,713.8 MT	29.9 MT[11]
MGO Consumption (Aux)	1,135.5 MT	3.6 MT

Based on the vessel's fuel consumption records for 2025 and on average performance data available in the literature for both main and auxiliary engines, the amount of potential waste heat has been estimated. The following section presents the calculated waste heat potential together with the methodologies adopted. These results form the basis for the subsequent techno-economic assessment.

Main Engine

By considering a Specific Fuel Oil Consumption (SFOC) of 175 g/kWh at 70-75% load for main engines, based on the manufacturer's datasheet[12], and by separating mechanical efficiency from waste heat according to the type of fuel consumed, it emerged that:

- when the main engines operate on HFO, the average mechanical efficiency is approximately 51%, with the remaining 49% released as waste heat. This analysis made it possible to quantify the amount of potential waste heat, which is estimated at 18,309,138.86 kWh per year;
- when the main engines operate on MGO, the average mechanical efficiency is approximately 48%, with the remaining 52% released as waste heat. This analysis made it possible to quantify the amount of potential waste heat, which is estimated at 35,121,731.43 kWh per year.

From the evaluation, it emerges that the total waste heat from main engines during annual operations can be considered equal to **53,430,870.3 kWh per year**. This thermal energy is released through different sources and in various forms.

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[10] Total consumption divided by the number of trips during which HFO was used for propulsion.

[11] Total consumption divided by the number of trips during which MGO was used for propulsion.

[12] S.E.M.T. Pielstick engine (Four stroke medium speed diesel engine Family), Link: *https://client-diesel.com/uploads/SEMT.pdf*, Accessed 12/03/2026.

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Based on the distribution proposed by Nader R. Ammar and Fathi A. Elwazzan[13], the waste-heat fractions of a typical marine Diesel engine can be represented as follows:

- 43% through the exhaust flue gases;
- 31% through the air-cooling system;
- 15% through the water-jacket cooling circuit;
- 9% via the lubricating-oil cooling circuit, and
- 1% as radiated heat lost to the engine room environment.

Auxiliary engine

By considering a Specific Fuel Oil Consumption (SFOC) of 198.5 g/kWh at 50% load for the auxiliary engines, based on an example Pre-Industrial Inspection Report of a containership equipped with the same auxiliary engine models[14], it was possible to estimate a mechanical engine efficiency of 42%, with the remaining 58% released as waste heat, corresponding to **4,700,112 kWh per year**.

For both the main and auxiliary engines, some of the waste heat is released from the vessel through the chimneys and flue gases, while the rest is dissipated through the cooling systems, such as the water jacket. Additionally, not all generated waste heat can be recovered due to the thermodynamic limitations inherent in heat-recovery systems. Further details will be provided in the techno-economic assessment of each technology, based on the most suitable waste-heat source and the recovery technology proposed.

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[13] Nader R. Ammar, and Fathi A. Elwazzan, Review of Energy Balance and Efficiency Enhancement Options for Marine Diesel Engines. *International Journal of Multidisciplinary and Current Research, Vol.8 (May/June 2020 issue). DOI: https://doi.org/10.14741/ijmcr/v.8.3.12*

[14] Pre-Purchase Inspection, Example Containership, 1st October 2022, Link: *https://www.idwalmarine.com/hubfs/Sample%20Reports/Pre-Purchase%20Inspections%20%28Sample%20reports%29/7.IdwalPrePurchaseReport_Container_Sample.pdf*, Accessed 12/03/2026.

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4 ORC analysis

The objective of this chapter is to study the feasibility of implementing on the selected vessels the ORC technology. It is necessary to create a realistic scenario to integrate ORC prototype on board, considering the system boundaries defined. A preliminary step is to evaluate the source, availability and working conditions of the waste heat, to check compatibility between ORC and each vessel, defining input and output characteristics.

Two main waste heat sources are the exhaust gases of the main engine and the cooling circuit of the auxiliary engines. Typically, shipping exhaust gases are characterized by a temperature around 300-400 °C, while the cooling line by a lower temperature around 80-100 °C.

Since ORC is a machine requiring higher temperatures, it is preferable to feed ORC with exhaust gas of the main engine. Furthermore, the main engine works continuously except when it is turned off during port operations, guaranteeing energy production by ORC. It is important to underline that coupling the ORC to the exhaust gas circuit of the main engine implies the integration of adaptable machinery such as heat exchangers to control and adjust the temperature at the optimal ORC working conditions.

According to D1.1, cycle thermal efficiency, defined as the rate between net electrical power (including pump consumption loss) and heat absorbed by the evaporator, is generally proportional to the heat source, its temperature and pressure, and the size of the system. Larger ORCs tend to be more efficient. In small-scale units, efficiency is typically limited by several factors, such as higher auxiliary consumption, higher thermal losses, and limited cycle optimization. As system size increases, these effects become less significant, leading to improved performance. Cycle efficiency of various ORC cycles designed for marine energy systems as a function of system net power output have been studied. Overall efficiencies can be expected in the range 5% to 25%. As reported by Chen et al.[15], thermal conditions can be influenced also by seasonality, and an average value of thermal efficiency of 10% can be taken as reference for this analysis.

The electrical power output of ORC prototype has been estimated to be 11.3 kWe. This data must be evaluated in relation to the typical on-board energy demand of different vessel categories.

Finally, it is important to define where the energy produced by ORC will be used, to estimate energy savings with a comparable target. The most realistic scenario is that ORC supplies electricity for many activities on board, sustaining light systems, refrigeration, etc. Therefore, the target for ORC electricity production is electrical production, which is typically demanded by auxiliary engines, excluding vessels equipped with shaft generator.

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[15] Chen, W., Xue, S., Lyu, L., Luo, W., & Yu, W. (2023). Energy Saving Analysis of a Marine Main Engine during the Whole Voyage Utilizing an Organic Rankine Cycle System to Recover Waste Heat. *Journal of Marine Science and Engineering*, *11*(1), 103. https://doi.org/10.3390/jmse11010103

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4.1 Fishery

4.1.1 Saving Assessment

Scenario 1

Considering TESEO operating conditions described in Chapter 3 and the ORC technical features, the thermal efficiency can be estimated to be approximately 10%, as previously described. Therefore, maximum theoretical energy demand from ORC prototype, assuming continuous work, is estimated to be 815,040.0 kWh/y. However, the maximum available waste heat quantity from exhaust gas on fishery is 35% of 640,246.0 kWh/y, which corresponds to 224,086.1 kWh/y. This means that the prototype is not compatible with working continuously at full power recovering just the exhaust gas of ME. To satisfy this boundary, the ORC should run below 27% of its power capacity.

If ORC would fit the waste heat availability requirements, it would exhibit an electrical power capacity of 11.32 kWe, and it would be possible to calculate the theoretical annual energy production knowing how many hours it can run annually. The main engine, as previously described, likely works at 50% load during navigation and 25% load during maneuvering for respectively 3,900 h/y and 2,800 h/y. Therefore, the maximum theoretical ORC energy production is given by multiplying 11.32 kWe by 6,700 h/y, which corresponds to 75,844 kWh/y.

Comparing the ORC energy capacity production, neglecting the exhaust gas availability constraint, with the average electrical energy produced by auxiliaries, which is 650,000 kWh/y, the annual energy savings of such system would be approximately 3.2%. Dividing this value by the density of MGO (11,825 kWh/kg), the fuel saved would be 6.4 t/y. Using the conversion factor of DEFRA 2024 for MGO (0.274 $kgCO_2e/kWh$), it is possible to estimate also the avoided GHG emissions, which corresponds to 20.8 tCO_2e/y. However, this solution seems to be unrealistic since the waste heat available is too low to run continuously the machine satisfying the original target of 20% energy savings. These results are resumed in Table 4.1.

Table 4.1: ORC saving assessment on fishery – Scenario 1

Parameter	Value	Unit
Maximum energy production	75,844	kWh/y
Energy savings	11.7	%
Fuel savings	6.4	t/y
Avoided GHG emissions	20.8	tCO_2e/y

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Scenario 2

The main problem to realize a scale-up of the prototype and install it on this fishery is the amount of waste heat available, which is too low to sustain a flexible integration of the prototype without a complex infrastructure and improvement of waste heat quantity. Moreover, it is remarkable that the ORC efficiency is quite low in these conditions, since low temperature levels at 150 °C are not suitable for high efficiency ORC.

The previous savings calculation is not compatible with the infrastructure present on fishery. The system would be downscaled to work at a limit of 27% of its full capacity, to match the waste heat energy availability. In this case, the ORC energy capacity production would be 20,852.5 kWh/y and comparing this amount with the electrical energy production by auxiliaries the savings are estimated to be 3.2%. Converting this value into fuel quantity, we find that the system could save 1.8 t/y of MGO, while avoiding 5.7 tCO_2e of GHG emissions.

Therefore, the simplest and most realistic scenario for the application on-board would be to realize a small-scale ORC able to work at low-medium temperature levels, with proper working fluid able to optimize efficiency, and able to satisfy the waste heat constraints.

Table 4.2: ORC saving assessment on fishery – Scenario 2

Parameter	Value	Unit
Maximum energy production	20,852	kWh/y
Energy savings	3.2	%
Fuel savings	1.8	t/y
Avoided GHG emissions	5.7	tCO_2e/y

4.1.2 Architecture constraints

The integration of ORC technology on board a fishery vessel presents significant potential for improving energy efficiency and reducing GHG emissions. However, its feasibility is subject to several architectural, operational, and environmental constraints unique to the fishing sector. This section outlines the key challenges associated with installation on board.

Fishing vessels, particularly the ones of medium size, have their distinguishing traits as compact engine rooms and restricted working space. Adding an ORC system with an evaporator, expander, pump, condenser, and control systems requires a dedicated volume which is not superficially accessible without major structural changes.

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Moreover, the vessels trim and stability can be altered by the weight and distribution of ORC parts. Placement of the equipment must be low in the hull, or areas where additional weight will guarantee operational safety or maneuvering dynamics. Further planning is still needed during retrofitting.

The integration of such a system comprehends also a discussion about thermal compatibility. Fishing operations typically involve prolonged periods at low engine loads during trawling, leading to lower exhaust gas temperatures (often 180–250°C). These temperatures may be marginal for efficient ORC operation, especially if high-boiling-point working fluids are used. Consequently, selecting a low-temperature-optimized ORC working fluid (e.g., R1233zd(E), R245fa, or newer HFOs) is essential. Moreover, the system must be designed to accommodate variable heat availability, which may fluctuate depending on engine operating mode.

ORC systems are ideal when operating continuously in steady-state operation. Fishing boats, however, have very variable mission profiles. This oscillation can limit the thermal input stability required by the ORC, especially in start-stop operation. Inconsistent thermal input could reduce efficiency or necessitate bypass and buffer systems to secure functionality. Furthermore, ORC systems are generally ill-suited for cyclical start-stop operation, leading to mechanical stress, degradation of the working fluid, and higher maintenance needs. Possible solutions would include adding a thermal buffer tank or intermediate heat exchanger to smooth the temperature profile into the ORC.

Feasibility is more favorable for new builds or vessels undergoing major retrofitting, and less so for smaller vessels with tight space and low thermal recovery potential. Nonetheless, if well-integrated, ORC systems can reduce auxiliary fuel use and emissions, especially when paired with energy-intensive equipment such as refrigeration or hydraulic winches.

4.1.3 Economic assessment

Analyzing financial aspects, the PBT is assessed by considering the fuel saving obtained in Scenario 2, which represents the more realistic operational condition for a small-scale ORC. When prototype is integrated on board, the economic parameter indicates very low attractiveness, as the resulting PBT is extremely high. However, it should be noted that original CAPEX refers to a prototype-scale system, designed for a larger energy demand than that available on the reference vessel. For real commercial implementation, the system would be downsized and designed to match the actual waste heat availability. At the current stage, it is not possible to estimate how much the costs would decrease after such redesign. Even if capital costs are not expected to scale linearly with the recovered energy, in this scenario they are considered linearly scaled with energy production, representing just 27% of prototype value, giving an approximate level of economic feasibility.

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Table 4.3: ORC economic parameters on fishery

Parameter	Value	Unit
Capex	66,186	€
Annual Saving	1,036	€/y
Simple PBT	>50	y

4.2 Cargo

4.2.1 Saving assessment

Scenario 1

Analyzing Scenario 1 of cargo, ORC receives waste heat from the main engine. In particular, the waste heat available on Ankie recoverable from exhaust gas is 583,924.43 kWh/y.

Observing the power profile and the tasks duration presented in the documentation shared by Attica, it is possible to calculate the maximum energy demand of the ORC. Considering only open sea transit and confined water transit hours, it is estimated that the ORC would be fed for approximately 5,250 h/y. Therefore, if considering thermal efficiency equal to 10%, the ORC energy demand would be around 594,300 kWh/y. This value is close to the available energy consumption from exhaust gases (583,924 kWh/y), therefore energetic compatibility could exist, but it would be necessary to lower the ORC load to guarantee safer match.

To calculate energy savings, the annual energy production from ORC technology is estimated. Being the electrical power output 11.32 kWe, the theoretical energy capacity of ORC on cargo vessel is 59,430 kWh/y. Since ORC energy production is designed to electricity generation, ORC productivity is compared to auxiliaries’ production. Considering that electricity production is 140,313 kWh/y, the energy savings should be 42.4%.

The amount of energy produced by ORC converted into fuel consumption corresponds to 5.0 t/y of fuel saved. The GHG emissions saved are equal to should be 16.3 tCO_2e/y.

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Table 4.4: ORC saving assessment on cargo – Scenario 1

Parameter	Value	Unit
Maximum energy production	59,430	kWh/y
Energy savings	42.4	%
Fuel savings	5.0	t/y
Avoided GHG emissions	16.3	tCO_2e/y

Scenario 2

ORC prototype performance could guarantee a satisfying result in terms of energy savings, since ORC would already overcome the target of 20% energy savings compared to electricity production. However, the results obtained refer to maximum energy productivity, considering continuous and stable energy flows. This means that several modifications could be applied to the prototype to guarantee good performance while reducing load and ensure safer match with waste heat available. Possible optimization strategies include adjusting the nominal capacity, improving heat exchange effectiveness Alternatively, the system could be downsized to reduce capital costs and achieve higher financial attractiveness.

In Scenario 2, the system is expected to be half-sized scaling linearly also energetic performance. This configuration allows the system to still achieve the target condition, while compacting size and architecture requirements. This adjustment would reduce the annual electricity generation to 29,715 kWh, setting the potential energy saving to 21.1%. Lastly, the fuel saving is estimated to be 2.5 t/y of MGO, while the avoided GHG emissions are 8.1 tCO_2e/y.

Table 4.5: ORC saving assessment on cargo – Scenario 2

Parameter	Value	Unit
Maximum energy production	29,715	kWh/y
Energy savings	21.1	%
Fuel savings	2.5	t/y
Avoided GHG emissions	8.1	tCO_2e/y

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4.2.2 Architecture constraints

Since the primary heat source for ORC is the exhaust gas from the main engine, the best solution should be to locate it in the engine room. This represents the most suitable solution to minimize thermal losses and better system controllability, by constructing shorter piping runs. Moreover, a heat exchanger can be directly integrated into the exhaust duct of the main engine. It is important also to integrate ORC with some essential systems already installed in the engine room, such as cooling water loops, electrical panels, and mechanical automation systems. Using these existing utilities can simplify the installation costs, wiring and instrumentation, and maintenance procedures. Integration is a remarkable constraint to achieve cost effective and operational feasible solution. The ORC involves pressurized working fluid that needs a safety and containment area. The engine room is already an isolated area with gas detection systems, fire suppression and systems for ventilation, but installing ORC could need to expand the danger zone. ORC turbines and pumps generate vibration, so it is important to install them where the deck strength is rated and where damping is already engineered, to avoid resonance issues and critical noise pollution.

However, it is important to check some structural constraints. The engine room could be fully occupied. Retrofitting requires clearance around main engine exhaust ducts. The heat exchanger must be installed without inducing excessive backpressure. The structural load of the vessel needs to be checked too. The weight of the full ORC system must be sustained by engine room decks, and a structural assessment is typically required for approval. Maintenance access must be guaranteed by leaving correct clearance around major components for inspection and services, offering easy disconnecting paths.

4.2.3 Economic assessment

As already done for fishery case, PBT is obtained by considering Scenario 2 conditions, in which capital costs are reduced to half of the prototype. However, ORC prototype Capex is still very high compared to annual savings, resulting in low attractive PBT.

Table 4.6: ORC economic parameters on cargo

Parameter	Value	Unit
Capex	122,566	€
Annual Saving	1,477	€/y
Simple PBT	>50	y

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4.3 Cruise

4.3.1 Savings assessment

Scenario 1

To assess the potential energy savings enabled by ORC technology on cruise vessels, it is assumed that the system is supplied with heat from the main-engine exhaust gases, which account for 43% of the total waste-heat output. From a theoretical perspective, this fraction corresponds to more than 23,100,000 kWh of waste heat per year.

Assuming a maximum ORC heat to power efficiency of 10%, which is also consistent with the value reported in "Energy Efficiency and Decarbonization Technical Guide"[16] and considering the operating profile previously introduced (8.8 hours per trip and 314 trips per year), the following considerations can be drawn:

- The thermal power available in the exhaust gases is estimated at circa 8,400 kW, far above the 110 kW thermal input capacity of the current ORC prototype. This clearly indicates that, for cruise-vessel applications, the ORC system would need to be scaled up to effectively exploit the available thermal power.
- A single prototype can only recover 1% of available waste heat, generating around 86.7 kWh of net electricity per trip, equivalent to around 27,200 kWh per year.
- This equates to just 0.78% of the electricity generated by the auxiliary engines, resulting in a reduction of only 0.01 tonnes of MGO and 0.02 tCO_2e per trip. This amounts to 2.3 tonnes of MGO and 7.5 tCO_2e per year.

Overall, the benefits of installing a single prototype on the Elyros cruise are negligible.

Table 4.7: ORC saving assessment on Cruise – Scenario 1

Parameter	Value	Unit
Maximum energy production	27,213	kWh/y
Energy savings	0.78	%
Fuel savings	2.3	t/y
Avoided GHG emissions	7.5	tCO_2e/y

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[16] U.S. Department of Transportation, Maritime Administration. Energy Efficiency and Decarbonization Technical Guide. November 2022. Link: https://www.maritime.dot.gov/sites/marad.dot.gov/files/2022-11/Energy%20Efficiency%20%26%20Decarbonization%20Technical%20Guide%20%2810-2022%29.pdf

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Scenario 2

To achieve significant results in terms of both project objectives and technological performance, a machine equivalent to five ORC modules must be installed (corresponding to a thermal input capacity of around 570 kW). According to the deliverable "WHR for Maritime Applications Catalogue", a system of this size should achieve an efficiency of 20% and would be capable of recovering more than 7% of waste heat from main engine flue gases.

In any case, as will be specified in the following section, the compatibility between the ORC system and the vessel must be verified in terms of both system dimensions and thermodynamic constraints.

Under these assumptions, the ORC unit would generate approximately 930 kWh of electric energy per trip, equal to 8.4% of the electric energy produced by the auxiliary engines. This corresponds to a reduction of 0.08 tons of MGO and 0.3 tCO_2e per trip, resulting in an annual reduction of 24.6 tons of MGO and 79.9 tCO_2e.

Table 4.8: ORC saving assessment on Cruise – Scenario 2

Parameter	Value	Unit
Maximum energy production	291,650	kWh/y
Energy savings	3.9	%
Fuel savings	24.6	t/y
Avoided GHG emissions	79.9	tCO_2e/y

4.3.2 Architecture constraints

As the ORC's primary heat source is the exhaust gas from the main engines, it would be best to locate the system in the engine room. This would minimise thermal losses and improve controllability of the system by reducing the length of the piping runs. Furthermore, a heat exchanger could be integrated directly into the main engine's exhaust duct.

It is also important to integrate the ORC with the essential systems already installed in the engine room, such as the cooling water loops, electrical panels, and mechanical automation systems. Using these existing utilities would reduce installation costs, simplify wiring and instrumentation, and streamline maintenance procedures. Integration is essential to achieving a cost-effective and operationally feasible solution.

The ORC involves pressurised working fluid, so a safety and containment area would be required. While the engine room is already an isolated area with gas detection, fire suppression, and ventilation systems, installing the ORC may require the danger zone to be expanded. As ORC turbines and pumps generate

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vibration, it is important to install them in areas where the deck strength is rated, and damping has been engineered to avoid resonance issues and critical noise pollution.

In conclusion, the proper installation of an ORC system requires careful verification of several structural and technical constraints. In particular:

- Space availability must be assessed to ensure that the equipment can be installed safely. In some cases, additional auxiliaries may be required, increasing the overall space demand.
- It is essential to verify that the ORC installation does not interfere with other systems that draw energy from the main-engine exhaust gases, such as turbochargers.
- The system must ensure that exhaust-gas temperature remains above the dew point after passing through the ORC heat exchanger, in order to avoid condensation of corrosive acidic components.
- A structural load assessment is also required to confirm that the vessel can accommodate the ORC equipment without compromising safety.
- The weight of the complete ORC system must be properly supported by the engine-room decks, and structural verification is typically required for class approval.
- Adequate maintenance access must be ensured by providing sufficient clearances around major components for inspection, servicing, and safe disconnection when needed.

4.3.3 Economic assessment

As was done for the fishery and cargo cases, PBT is obtained by considering Scenario 2. The ORC prototype Capex is obtained by multiplying the Capex by three (according to the most feasible scenario). It should be noted that the cost of a larger ORC does not increase linearly, so it is expected that the CAPEX cost will be lower and the economic outlook will be slightly better in the real world.

Table 4.9: ORC economic parameters on Cruise

Parameter	Value	Unit
Capex	1.225.660	€
Annual Saving	14,450	€/y
Simple PBT	< 75	y

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5 SR&D Machine analysis

The integration of a sorption refrigeration and desalination machine presents a reliable opportunity to valorise low-grade waste heat to reduce the auxiliary engine load for cooling and freshwater production. Considering the technical characteristics of the module under evaluation, the condenser, which is connected to freshwater production, as well as the evaporator, connected to cooling production, exhibit 20 kW of nominal capacity. As reported by the experimental campaign of CNR[17], the electrical COP for cooling is 20, while for desalination it reduces to 10.

To evaluate the benefits of installing this technology on board a vessel, it is necessary to calculate the amount of electrical energy that a conventional chiller would require generating the same cooling output. For this comparison, an average COP equal to 3 was assumed for the chiller[18]. Therefore, for the same thermal output (cooling), the SR&D unit requires less electrical input than a conventional chiller. This translates into a reduction in fuel consumption in the auxiliary engines, due to the lower electrical power demand, and consequently a decrease in both fuel use and CO_2e emissions. For completeness, the chiller (or equivalent installed unit) can be kept in place as a backup system in case of failure, maintenance or critical conditions. At the same time, a sweater reverse osmosis (SWRO) has been considered as benchmark to assess the saving associated with the desalination process. Specifically, as reported by Tsai et al.[19], experimental studies demonstrate that the Specific Energy Consumption of Sea Water Reverse Osmosis Integrated with Membrane Distillation and Pressure–Retarded Osmosis Processes ranges between 4 and 10 kWh/m^3 of freshwater produced, depending on set conditions. On the other hand, typical self-consumption values for adsorption units stay below 2 kWh/m^3[20]. In order to estimate the annual energy consumption of the benchmark RO unit, three different freshwater production conditions have been set:

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[17] A. Frazzica, S. Vasta, A. Bonanno, V. Palomba, M. Calò, W. Mittelbach; Development and experimental characterization of an innovative adsorption chiller configuration for industrial cooling provision; Consiglio Nazionale delle Ricerche, Istituto di Tecnologie Avanzate per l'Energia, May 2026.

[18] Luvisminda, M.; April, M. Effect of Perforated Metal Shield in the Operation of a Marine Refrigeration System with Waste Heat Recovery Channel. E3S Web of Conferences 488, 03011 (2024),https://doi.org/10.1051/e3sconf/202448803011

[19] Tsai, S.-C., Huang, W.-Z., Lin, G.-S., Wang, Z., Tung, K.-L., & Chuang, C.-J. (2022). Evaluation of the Specific Energy Consumption of Sea Water Reverse Osmosis Integrated with Membrane Distillation and Pressure–Retarded Osmosis Processes with Theoretical Models. *Membranes*, *12*(4), 432. https://doi.org/10.3390/membranes12040432

[20] Kyaw Thu, A. Chakraborty, B.B. Saha, Won Gee Chun, K.C. Ng, Life-cycle cost analysis of adsorption cycles for desalination, Desalination and Water Treatment, Volume 20, Issues 1–3, 2010, Pages 1-10, ISSN 1944-3986, https://doi.org/10.5004/dwt.2010.1187

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- 7,500 m^3/y on fishery;
- 5,000 m^3/y on cargo;
- 120,000 m^3/y on cruise.

The most suitable heat source on vessel is the jacket water outlet of the main engine, which typically reaches 85-90 °C during activities such as trawling on fishery. The availability of jacket water waste heat depends on main engine function. If the main engine is turned on, a continuous heat flow is guaranteed; otherwise, if it is turned off, energy input is not present.

At cited in D1.1, current cooling adsorption units in Europe go up to a maximum power rating of 100 kW. Due to the system being based on sorbent beds, the technology is more feasibly scaled down than scaled up (differently from absorption chillers where larger volumes of liquid for absorption are more economically viable).

The economic assessment developed for SR&D technology refers solely to the alternative production of cooling and freshwater, as their combined production within the ZHENIT prototype has not yet been fully tested. The combined operating mode is expected to be more advantageous because, with the same capital investment, it would allow simultaneous production for two different purposes with only a limited increase in thermal and energy demand. However, the potential cost savings of this combined configuration cannot be reliably quantified through a purely theoretical approach, unlike those associated with alternative solutions.

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5.1 Fishery

5.1.1 Saving assessment

Scenario 1

As previously described, the waste heat from ME is approximately 640,246.0 kWh/y. Referring to the document provided by Miller et al.[21], 25% of this heat quantity is represented by jacket water component. Therefore, 160,061.5 kWh/y of waste heat can feed the Adsorption Machine.

The thermal power necessary to run the machine should be close to 40 kW, requiring a total energy demand of 268,000 kWh/y, which is compatible with waste heat availability from main engine.

The estimated electrical self-consumption power for cooling is 1 kW, while for desalination is 2 kW; therefore, considering 6,700 h/y as main engine working time, the maximum auxiliary energy demand should be 6,700 kWh/y and 13,400 kWh/y respectively.

Analyzing the cooling production, 20 kW of cooling power are registered at the evaporator, guaranteeing at full capacity 134,000 kWh/y of thermal energy production. This value represents the equivalent cooling production of a chiller mounted on board, assuming a COP equal to 3. Considering the difference between the equivalent chiller consumption and the prototype adsorption machine self-consumption, equal to 37,967 kWh/y, it is possible to estimate the percentage energy savings, comparing this value with the auxiliary average annual electrical energy consumption, equal to 5.8%. Prototype adoption corresponds to 3.2 t/y of fuel saved, while the avoided GHG emissions are 10.4 tCO_2e/y.

Table 5.1: SR&D cooling mode saving assessment on fishery – Scenario 1

Parameter	Value	Unit
Maximum cooling production	134,000	kWh/y
Energy savings	5.8	%
Fuel savings	3.2	t/y
Avoided GHG emissions	10.4	tCO_2e/y

Assessing the desalination mode, an equivalent SWRO unit of 134,000 kWh capacity is assumed, with a specific energy consumption set at 5 kWh/m^3. Given a COP of 10, the SR&D machine consumption is

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[21] Miller, T.; Durlik, I.; Kostecka, E.; Kozlovska, P.; Jakubowski, A.; Łobodzińska, A. Waste Heat Utilization in Marine Energy Systems for Enhanced Efficiency. *Energies* **2024**, *17*, 5653. https://doi.org/10.3390/en17225653

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13,400 kWh/y, registering annual energy savings equal to 24,100 kWh/y. The fuel saved is 2.0 t/y, while the GHG emissions avoided are 6.6 tCO2e/y.

Table 5.2: SR&D desalination mode saving assessment on fishery – Scenario 1

Parameter	Value	Unit
Maximum freshwater production	7,500	m^3/y
Energy savings	3.7	%
Fuel savings	2.0	t/y
Avoided GHG emissions	6.6	tCO_2e/y

No scenario 2 is developed for the fishery case, since both cooling and freshwater requirements onboard are fixed parameters, and the prototype could theoretically satisfy their demand. Upsizing the prototype would be possible, considering the waste heat available, but it would be less necessary than for other technologies studied in this work, which produce directly electricity for many purposes.

5.1.2 Architecture constraints

The integration of the adsorption machine on a fishery requires the evaluation of several possible technical and architectural constraints, stemming from space limitations, marine operating conditions, thermal coupling, system control complexity. Firstly, the system needs stable waste heat source, as already addressed, to produce freshwater and cooling. Navigation and fishing phases are different tasks which correspond to different energy loads and operating profiles. Irregular driving conditions could need the integration of TES for enhancing load stability.

From an architectural point of view, the adsorption system comprises a generator, a condenser, an evaporator and adsorber beds, forming a bulky unit that could represent a limitation on-board small-scale vessel such as fishery. Its placement must consider limited floor space, especially in crowded engine rooms or underdeck compartments, reinforcement and custom mounts. At the same time, the cold demand zone and the freshwater targets could benefit from short distances with respect to the machine installation. On the cold side, the chilled water distribution system must be dimensioned to handle low flow rates (typically 0.5 – 1.5 m^3/h) and maintain the desired temperature range (typically 3 – 7 °C) in refrigeration applications. Integration with desalination units (e.g., MED or low-temperature distillation) is also feasible, where evaporator cooling supports condensation cycles, but this increases system complexity and demands precise thermo-hydraulic balance.

Challenges to improve performances while finding the correct positioning and structure on-board lie in improving the machine’s intrinsic characteristics can the system achieve higher energy savings beyond what is dictated by waste heat availability.

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5.1.3 Economic assessment

Table 5.3 shows the economic assessment of the SR&D machine integration. The annual savings consider the range between cooling and desalination modes, reflected in the simple PBT, which is 7.8 to 12.3 years, resulting in a feasible solution for fishery application.

Table 5.3: SR&D economic parameters on fishery

Parameter	Value	Unit
Capex	14,400	€
Annual Saving	3,210 – 2,038	€/y
Simple PBT	7.8 – 12.3	y

5.2 Cargo

5.2.1 Savings assessment

Scenario 1

On cargo vessel, the best available waste heat source around that flow condition is again the jacket water loop derived from main engine. Firstly, the compatibility between adsorption machine energy demand and waste heat from water jacket circuit must be checked. Considering prototype characteristics and 5,250 h/y as main engine operating hours, the total annual SR&D self-consumption for cooling is 5,250 kWh/y. As previously stated, 417,088.9 kWh/y is the quantity derived from water jacket circuit that can feed the adsorption machine. This means that the prototype is clearly compatible with the energy available on cargo.

The thermal energy demand of the SR&D unit is compatible with the waste heat available, since it has been estimated to be around 210,000 kWh/y.

Analyzing the cooling production, 20 kW of cooling power are registered at the evaporator, guaranteeing at full capacity 105,000 kWh/y of cooling production. Assuming the displacement of an equivalent chiller with COP equal to 3, the difference between the equivalent chiller consumption and the prototype self-consumption is equal to 29,750 kWh/y. The energy saving compared to auxiliaries' production is equal to 21.2%.

The conversions from energy consumption to fuel consumption and to avoided GHG emissions are obtained using DEFRA conversion factors, and they are equal to 2.5 t/y of MGO and 8.2 tCO_2e/y respectively.

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Table 5.4: SR&D cooling mode saving assessment on cargo – Scenario 1

Parameter	Value	Unit
Maximum cooling production	105,000	kWh/y
Energy savings	21.2	%
Fuel savings	2.5	t/y
Avoided GHG emissions	8.2	tCO_2e/y

Considering the desalination modality, an equivalent SWRO unit of 105,000 kWh capacity at the condenser is assumed, with a specific electrical energy consumption set at 5 kWh/m^3. Given a COP of 10, the SR&D machine consumption is 10,500 kWh/y, registering annual energy savings equal to 14,500 kWh/y. The fuel saved is 1.2 t/y, while the GHG emissions avoided are 4.0 tCO2e/y.

Table 5.5: SR&D desalination mode saving assessment on cargo – Scenario 1

Parameter	Value	Unit
Maximum freshwater production	5,000	m^3/y
Energy savings	10.3	%
Fuel savings	1.2	t/y
Avoided GHG emissions	4.0	tCO_2e/y

As done for the fishery case, scenario 2 is not developed for cargo analysis, since both cooling and freshwater demands are already met by the prototype. Upsizing the prototype would be possible, considering the waste heat available, but it would be less necessary than for other technologies studied in this work, which produce directly electricity for many purposes.

5.2.2 Architecture constraints

Given the architecture specifics described in D4.1, a total footprint ranging from 2 to 4 m^2 of floor area, and a height approximately of 2 m is considered. On many cargo vessels, this size is manageable in the engine room or technical spaces but must be checked against ship layout and other systems. Ideally, the unit should be located close to the main or auxiliary engine jacket water circuits to minimize thermal losses and avoid long piping runs. For effective thermal integration, connections to both hot water sources (jacket water loop) and the chilled water or freshwater circuits (depending on whether refrigeration or desalination is prioritized) are required, along with a heat rejection pathway, often connected to seawater cooling. Structurally, the installation must be resistant to vibrations and marine corrosion, potentially requiring mounting on dampers and the use of marine-grade materials. The area must also allow for proper drainage and access for maintenance activities such as filter changes and silica gel replacement. The system should also be connected to the vessel's control or energy management systems for proper monitoring and operational scheduling. While integration is technically viable, it demands coordinated planning with ship engineers to ensure thermal loops are correctly managed, buffer systems or switchovers are in place to alternate between main and auxiliary engines, and crew members are trained to operate and maintain the unit. Overall, the adsorption machine can be successfully integrated into the vessel's architecture with moderate effort and offers a promising solution for improving onboard energy efficiency.

5.2.3 Economic assessment

The economic assessment of the SR&D machine integration is presented below, showing encouraging results for its adoption onboard. The fuel savings range refers to cooling and desalination mode alternatively. The simple PBT results in more than 10 years, representing a realistic solution for valorising waste heat available on cargo only in case of combined production of freshwater and cooling.

Table 5.6: SR&D economic parameters on cargo

Parameter	Value	Unit
Capex	14,700	€
Annual Saving	2,515 – 1,226	€/y
Simple PBT	9.9 - 20.4	y

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5.3 Cruise

5.3.1 Savings assessment

Scenario 1

As previously described for the Elyros Cruise, the waste heat generated by the MEs is approximately 53,430,870 kWh/year. However, the quantity available through the jacket water circuit is only 15% of this. Therefore, 8,205,195 kWh of waste heat can be used to power the adsorption machine for a whole year. Considering a typical route, the available waste heat is around 26,130 kWh per trip.

With a cooling capacity of 20 kWth and an average journey duration of 8.8 hours, the system is able to generate approximately 175.1 kWh of cooling energy per trip. To produce this amount of cooling, the solution requires roughly 8.8 kWh of energy.

To assess the benefits of implementing this solution, it is useful to consider the performance of a hypothetical onboard chiller with a COP of 3. Producing the same amount of cooling energy with such a chiller would require 58.4 kWh. Therefore, the net energy saving amounts to around 49.6 kWh per trip.

This corresponds to a 0.4% reduction in electricity generated by the AEs and translates into a decrease of approximately 0.004 tonnes of MGO and 0.014 tCO_2e per trip, equivalent to about 1.3 tonnes of MGO and 4.3 tCO_2e annually.

Overall, the benefits of installing a single prototype on the Elyros cruise are negligible.

Table 5.7: SR&D cooling mode saving assessment on Cruise – Scenario 1

Parameter	Value	Unit
Maximum cooling production	54,976	kWh/y
Energy savings	0.4	%
Fuel savings	1,3	t/y
Avoided GHG emissions	4,3	tCO_2e/y

On the other hand, if the SR&D unit operates as a desalination unit, considering the same amount of heat in input, it should be able to produce 9.8 m^3 of fresh water per trip. To produce this amount of water, 17.5 kWh of electric energy will be required per trip.

In order to evaluate the advantages of implementing this solution, it is helpful to consider the performance of a hypothetical onboard SWRO chiller with an SEC of 4 kWh/m^3. Producing the same amount of water with such a unit would require 39.2 kWh. Therefore, the net energy saving would be around 29.4 kWh per trip.

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This corresponds to a 0.3% reduction in electricity generated by the AEs, which translates into a decrease of around 0.002 tonnes of MGO and 0.008 tCO_2e per trip, equivalent to approximately 0.8 tonnes of MGO and 2.5 tCO_2e annually.

Overall, the benefits of installing a single prototype on the Elyros cruise are negligible.

Table 5.8: SR&D desalination mode saving assessment on Cruise – Scenario 1

Parameter	Value	Unit
Maximum water production	3,077	m^3/y
Energy savings	0.3	%
Fuel savings	0.8	t/y
Avoided GHG emissions	2.5	tCO_2e/y

Scenario 2

To achieve significant results, both in terms of meeting project objectives and technological performance, at least one machine equivalent to thirty SR&D prototype modules (corresponding to a thermal input capacity of 600 kW) must be installed. A system of this size would be capable of recovering 20% of the technically recoverable waste heat from main-engines jacket water circuit.

With a thermal output of 600 $kW_{cooling}$, the system is able to generate approximately 5,252.5 kWh of cooling energy during an average journey. To produce this amount of cooling, the solution requires roughly 262 kWh of electricity.

As done previously, the benefits of implementing this solution were assessed by comparing it with a hypothetical onboard chiller operating with a COP of 3. Producing the same amount of cooling energy with such a chiller would require 1,750 kWh. Therefore, the net energy saving amounts to around 1,500 kWh per trip.

This saving corresponds to a 13,5% reduction in electricity generated by the auxiliary engines (AEs) and translates into a decrease of approximately 0.13 tonnes of MGO and 0.4 tCO_2e per trip, equivalent to about 39.4 tonnes of MGO and 127 tCO_2e annually.

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Table 5.9: SR&D cooling mode saving assessment on Cruise – Scenario 2

Parameter	Value	Unit
Maximum cooling production	1,649,290	kWh/y
Energy savings	13,5	%
Fuel savings	39,4	t/y
Avoided GHG emissions	127	tCO_2e/y

If the same unit is switched to desalination and water production, it should be able to produce 294.0 m^3 of fresh water per trip. To produce this amount of water, 525.3 kWh of electric energy will be required per trip.

As done previously, the benefits of implementing this solution were assessed by comparing it with a hypothetical onboard SWRO chiller with an SEC of 4 kWh/m^3. Producing the same amount of water with such a unit would require 1,175.9 kWh. Therefore, the net energy saving would be around 882.0 kWh per trip.

This corresponds to an 8.0% reduction in electricity generated by the AEs, which translates into a decrease of around 0.074 tonnes of MGO and 0.24 tCO_2e per trip, equivalent to approximately 23.3 tonnes of MGO and 75.9 tCO_2e annually.

Table 5.10: SR&D desalination mode saving assessment on Cruise – Scenario 2

Parameter	Value	Unit
Maximum water production	92,311,00	m^3/y
Energy savings	8.0	%
Fuel savings	23.3	t/y
Avoided GHG emissions	75.9	tCO_2e/y

5.3.2 Architecture constraints

Once verified against the vessel's layout and other systems, an SR&D machine with a capacity of 600 kW should be installed in engine rooms or technical spaces. Ideally, the unit should be located close to the main engine jacket water circuits in order to minimise thermal losses and avoid long piping runs. To ensure effective thermal integration, connections to both the jacket water loop (the hot water source) and the chilled water or freshwater circuits (depending on whether refrigeration or desalination is

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prioritised) are required, as well as a heat rejection pathway, which is often connected to seawater cooling.

Structurally, the installation must be resistant to vibrations and marine corrosion, which may require mounting on dampers and the use of marine-grade materials. The installation area must also allow for proper drainage and provide access for maintenance activities such as filter changes and silica gel replacement. The system should also be connected to the vessel's control or energy management systems for proper monitoring and operational scheduling. While integration is technically feasible, coordinated planning with ship engineers is required to ensure that thermal loops are managed correctly, that buffer systems or switchovers are in place to alternate between the main and auxiliary engines, and that crew members are trained to operate and maintain the unit. Overall, with moderate effort, the adsorption machine can be successfully integrated into the vessel's architecture and offers a promising solution for improving onboard energy efficiency.

5.3.3 Economic assessment

As was done for the fishery and cargo cases, PBT is obtained by considering Scenario 2. The SR&D prototype Capex is obtained by multiplying the CAPEX by thirty (according to the most feasible scenario). It should be noted that the cost of a larger SR&D does not increase linearly, so it is expected that the CAPEX cost will be lower and the economic outlook will be slightly better in the real world.

Table 5.11: SR&D economic parameters on Cruise

Parameter	Value	Unit
Capex	441,000	€
Annual Saving	13,700 – 23,150[22]	€/y
Simple PBT	19 – 32	y

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[22] The amount of energy saved depends on the configuration of the SR&D unit. Higher annual savings and lower PBT are obtained if the SR&D Unit works as a sorption unit. The machine provides lower economic benefits if it works as a desalination unit.

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6 IEE analysis

The integration of Isobaric Expansion Engine (IEE) on shipping vessels requires a deep evaluation of available waste heat streams to ensure alignment with onboard thermal energy demands and operational profiles. The IEE prototype, as described in D2.2., is classified as Worthington type, which suits better for low-medium temperature and for power generation at vessel scale. This prototype, referring to D4.1, operates with low-grade temperature heat input, between 80 – 90 °C, producing mechanical energy or electrical energy via isobaric expansion of the working fluid. Given these constraints, the selection of the waste heat source must be addressed in main engine operations. The main engine represents the best feeding solution compared to auxiliaries, since it delivers energy in continuous mode. Jacket water loop and exhaust gas are the possible waste heat sources of main engine. The jacket water system presents a higher compatibility for IEE, since the temperature levels are similar, avoiding the integration of heat exchangers and other components that would reduce the recovery efficiency. This heat form is continuously available during navigation and maneuvering, even if the engine is running at moderate or scarce loads, ensuring a reliable and stable supply of heat for IEE.

The IEE under investigation has a thermal demand of 25 kW, but no precise information about mechanical efficiency is available to convert heat into mechanical work, and finally to electricity. Many variables affect the efficiency of this engine. Worthington type IEE is affected by both thermodynamic and geometrical conditions that determine work losses. Typically, a higher delta temperature between waste heat and cooling circuit and a higher delta pressure between evaporation and condensation increase the useful work. The fluid type and its mass flow deliver a certain power output. Operating frequency, compression volume and expansion volume of the cylinder affect cycle effective work.

Referring to the experimental testing campaign on three different configurations of Worthington type IEE performed by Glushenkov and Kronberg[23], the engine process is far from an ideal thermodynamic process. The experimental and theoretical efficiency is low in comparison with the maximum possible efficiency for the given temperatures (25–40 % of the Carnot efficiency). This low relative efficiency is since, for the working fluid used and the operating conditions, thermodynamics imposes severe limits on the amount of heat exchanged in the recuperator. Therefore, it can be assumed an efficiency of 6%, as the best result obtained for the test of reference at given conditions, which is a realistic value for typical low-grade temperature level IEEs. In this case, considering null electrical losses in the transformation of mechanical power to electrical power, the power capacity of IEE would be approximately 1.5 kWe.

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[23] M. Glushenkov, A. Kronberg, Experimental study of an isobaric expansion engine-pump – Proof of concept, Applied Thermal Engineering, Volume 212, 2022, 118521, ISSN 1359-4311, https://doi.org/10.1016/j.applthermaleng.2022.118521. (https://www.sciencedirect.com/science/article/pii/S1359431122004744)

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6.1 Fishery

6.1.1 Saving assessment

Scenario 1

Regarding fishery operating conditions, the maximum energy consumed by IEE assuming continuous work at full load is 167,500 kWh/y, which is close, but not completely compatible, with the water jacket energy availability, which is 160,061.5 kWh/y on TESEO.

Given the prototype working conditions, the electrical net capacity is 1.5 kWe. The operating hours, as discussed in the previous paragraphs, are 6,700 h/y.

Neglecting the waste heat constraint, the total amount of annual electrical energy produced by IEE could be around 10,050 kWh/y. In the case of electrical integration, the IEE could satisfy just a little part of the energy demand covered by auxiliaries. We compare the electrical energy produced by IEE with auxiliary energy consumption to estimate the annual savings, which are 1.6%. The fuel saved, applying the SFC of auxiliaries to the calculation, is equal to 0.9 t/y. The GHG emission reduction is obtained using DEFRA 2024 emission factor for MGO, and it is 2.8 tCO_2e/y.

Table 6.1: IEE saving assessment on fishery – Scenario 1

Parameter	Value	Unit
Maximum energy production	10,500	kWh/y
Energy savings	1.6	%
Fuel savings	0.9	t/y
Avoided GHG emissions	2.8	tCO_2e/y

Scenario 2

The energy demand mismatch between the IEE and the jacket water could be overcome by running the machine at lower power. Indeed, the difference between the theoretical power capacity and the power capacity compatible with the on-board infrastructure is little. To fill the gap, it is sufficient to run the machine at 96% of its full capacity, since working at full power in continuous mode would be an unrealistic scenario.

Referring to this configuration, the new theoretical energy production would be 9,604.7 kWh/y. Results would slightly change, being translated into energy saving of 1,5%, compared to electrical production by auxiliaries. The MGO fuel saving would be around 0.8 kg/y, while the GHG emissions saved would be 2.6 tCO_2e/y.

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The target of 20% energy saving would correspond to a new IEE energy production of 50,700 kWh/y, resulting in 7.57 kWe of electrical power output. Therefore, with the assumed efficiency, the IEE thermal input required would be only 126.11 kWth, while the energy consumption would be 845,000 kWh/y. This condition represents an unrealistic scenario. To improve the IEE performance, it would be necessary to improve the efficiency of the system. However, this technology is not designed to achieve much higher performance. Therefore, the technical feasibility of IEE on fishery is considered negative.

6.1.2 Architecture constraints

The installation of IEE on a fishery vessel, recovering waste heat from water jacket circuit and converting it into electrical energy, involves several technical and architectural constraints. The low temperature level limits the thermodynamic potential of the machine, requiring better thermal efficiency and necessitating heat exchangers and fluids compatible with the system. The IEE requires the installation of a closed-loop heat recovery circuit, coupling the engine with a generator. This setup must fit with the tight confines of the engine room without interfering with critical equipment or obstructing maintenance access

In the case of a Worthington-type IEE, the system operates through two reciprocating cylinders (expansion and compression) working in an isobaric regime. This configuration imposes specific geometric constraints, as the unit requires alignment of pistons, linkage mechanisms, and ancillary valves that may increase the footprint compared to rotary or scroll-based expanders. The mechanical coupling between the expansion chamber and the generator should be vibration-isolated to prevent structural resonance and fatigue in the vessel's hull.

Thermodynamically, the low-grade heat (around 80–100 °C) available from the cooling water circuit limits the achievable pressure ratio and thus the overall efficiency, typically below 10% under real operating conditions. To maximize energy recovery, the system should employ fluids with high vaporization enthalpy at low pressure (e.g., R245fa, R1233zd, or low-GWP refrigerants) and high-effectiveness heat exchangers to minimize temperature losses across the circuit. Integration with a thermal buffer or regenerator may help stabilize performance during variable engine loads typical of fishery operations.

From an architectural standpoint, minimizing the mass and volume of the recovery loop is essential. Indeed, modular heat exchangers and an engine-mounted skid arrangement can simplify retrofitting and maintenance. Finally, adequate thermal insulation and condensate management must be ensured to prevent humidity and corrosion issues within the engine room.

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6.1.3 Economic assessment

Economic viability for this machinery is quite favorable thanks to very low CAPEX. Consequently, simple PBT is very attractive. However, this faces technical issues due to high energy demand and low efficiency, negatively influencing the overall replication potential on fishery.

Table 6.2: IEE economic parameters on fishery

Parameter	Value	Unit
Prototype Capex	810	€
Annual Saving	391	€/y
Simple PBT	2.1	y

6.2 Cargo

6.2.1 Saving assessment

Scenario 1

Under the assumed working conditions, IEE receives waste heat from water jacket of ME, which operates mainly during open sea transit and confined water transit for cargo operations. The total amount of hours that ME can feed IEE is 5,250 h/y. Therefore, the estimated IEE energy demand is about 131,250 kWh/y. The available energy from the water jacket loop connected to main engine, as previously described, is 417,089 kWh/y. This means that the energy available from water jacket circuit is largely compatible with the integration of IEE on cargo.

Since IEE is designed to produce electricity, the comparative analysis to estimate savings should be performed assessing auxiliary consumptions. Similarly to previous cases, the total annual energy consumption from auxiliaries on cargo (excluding loading/unloading operations) is 140,313.60 kWh/y.

Comparing auxiliary baseline with IEE scenario, it is found that the total annual savings are estimated to be 5.6 % with respect to auxiliary consumptions. This corresponds to 0.7 t of fuel saved, and 2.2 tCO_2e of avoided GHG emissions.

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Table 6.3: IEE saving assessment on cargo – Scenario 1

Parameter	Value	Unit
Maximum energy production	7,875	kWh/y
Energy savings	5.6	%
Fuel savings	0.7	t/y
Avoided GHG emissions	2.2	tCO_2e/y

Scenario 2

IEE prototype covers just a small portion of electricity production by auxiliaries. IEE efficiency could be difficultly improved due to technical limits. In order to achieve higher performance, more than one IEE module would be necessary. The waste heat available on-board could sustain triple-module IEE, which total power consumption would be around 75 kW. The new energy consumption would be equal to 393,750 kWh, still below the waste heat availability threshold. Therefore, the new energy production would be 23,625 kWh, corresponding to 17% of energy saving compared to auxiliaries' electricity production. This corresponds to approximately 2.0 t of fuel saved and 6.5 tCO_2e of avoided GHG emissions.

Although this value remains slightly below the 20% energy saving target considered in the project, it demonstrates that a modular scale-up approach can significantly enhance the performance of the technology. Additional improvements could potentially be achieved through further optimization of heat-exchanger design, improved integration with the vessel's cooling systems, or by recovering heat from additional low-temperature sources onboard.

Table 6.4: IEE saving assessment on cargo - Scenario 2

Parameter	Value	Unit
Maximum energy production	23,625	kWh/y
Energy savings	17	%
Fuel savings	2,0	t/y
Avoided GHG emissions	6.5	tCO_2e/y

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6.2.2 Architecture constraints

Integrating an IEE into a cargo vessel like MV Ankie presents several space and architectural constraints that must be carefully considered to ensure feasibility and operational reliability.

The IEE unit requires dedicated space close to both the jacket water loop (the waste heat source) and the mechanical load it will drive, such as seawater or LT cooling pumps. This proximity reduces losses and minimizes the complexity of piping and shaft alignment. The IEE must be installed on a stable and vibration-tolerant platform, ideally on the engine room or a nearby machinery space, to withstand vibrations and ship motions. The unit's footprint is typically moderate (around the size of a small compressor), but space must also be allocated for thermal insulation, piping, valves, and access for maintenance.

Another architectural constraint involves the cooling sink, which is essential for the IEE's thermodynamic cycle. The IEE works by expanding a working fluid from a high temperature (around 90 °C, typically from the main engine's jacket water) to a lower temperature (84 °C), and then transferring that heat to a cooler fluid at 20–26 °C. Without a cooling sink, the temperature gradient would collapse, and the engine would stop producing mechanical energy. The sink acts like a thermal drain, allowing the cycle to restart continuously. On ships, this sink is often provided by seawater cooling loops or the vessel's low-temperature circuit. However, the availability of this cooling fluid is not always guaranteed, especially in tropical climates or during maintenance phases. As a result, space must also be allocated for integrating heat exchangers, piping, and flow control units that connect the IEE to this cooling infrastructure. In some cases, boosting or auxiliary pumps may be needed, adding further spatial and energy demands.

6.2.3 Economic assessment

Economic assessment is based on Scenario 2 outcomes. The main hypothesis is that prototype could be tripled-sized to achieve better energy savings, exploiting more waste heat available. Enlarging the size of the machine implies increasing associated costs. Generally, CAPEX does not increase linearly with dimension; however, in this case, it is assumed that costs scale linearly and represent three times the original prototype value. This allows to achieve better technical results, while maintaining simple PBT indicators attractive.

Table 6.5: IEE economic parameters on cargo

Parameter	Value	Unit
Capex	2,430	€
Annual Saving	391	€/y
Simple PBT	6.2	y

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6.3 Cruise

6.3.1 Savings assessment

Scenario 1

As previously described, the waste heat generated by the MEs amounts to approximately 53,430,870 kWh per year. However, only 15% of this is available through the jacket water circuit. Therefore, 8,205,195 kWh of waste heat could power the Isobaric Expansion Engine for a year. On a typical route, around 26,130 kWh of waste heat is available per trip.

With a thermal input of 25 kWth, an estimated thermodynamic efficiency of 6%, and an average journey duration of 8.8 hours, the following conclusions can be drawn:

- The thermal power available in the exhaust gases is estimated at 2,985 kW, which is far above the 25 kW thermal input capacity of the current IEE prototype. This clearly indicates that the IEE system would need to be scaled up for cruise-vessel applications in order to effectively exploit the available thermal power.
- A single prototype can only recover 0.8% of available waste heat, generating around 13.1 kWh of net electricity per trip, equivalent to around 4,123 kWh per year.
- This equates to just 0.12% of the electricity generated by the auxiliary engines, resulting in a reduction of only 0.001 tonnes of MGO and 0.004 tCO_2e per trip. This amounts to 0.3 tonnes of MGO and 1.1 tCO_2e per year

Overall, the benefits of installing a single prototype on the Elyros cruise are negligible.

Table 6.6: IEE saving assessment on cruise – Scenario 1

Parameter	Value	Unit
Maximum energy production	4,123	kWh/y
Energy savings	0.12	%
Fuel savings	0.3	t/y
Avoided GHG emissions	1.1	tCO_2e/y

Scenario 2

The IEE prototype only covers a small proportion of electricity production by auxiliaries. Improving IEE efficiency could be difficult due to technical limitations. To achieve higher performance, more than one IEE module would be necessary. The available waste heat on board could sustain a twenty-five module IEE with a total thermal power consumption of 625 kW.

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Therefore, the new energy production would be 328.3 kWh per trip, which corresponds to an energy saving of 3% compared to the electricity production of the auxiliaries during one trip. This equates to around 0.03 tonnes of MGO saved and 0.1 tonnes of avoided GHG emissions per trip. Over the course of a year, this would equate to a reduction of 8.7 tonnes of MGO and avoided emissions of 28.1 tCO_2e.

While this value remains below the 20% energy saving target set out in the project, it shows that a modular scaling-up approach can greatly improve the technology's performance. Further improvements could potentially be achieved by optimising the design of the heat exchanger, improving its integration with the vessel's cooling systems or recovering heat from additional low-temperature sources on board.

Table 6.7: IEE saving assessment on cruise - Scenario 2

Parameter	Value	Unit
Maximum energy production	103,080	kWh/y
Energy savings	3	%
Fuel savings	8.7	t/y
Avoided GHG emissions	28.1	tCO_2e/y

6.3.2 Architecture constraints

As mentioned previously with regard to cargo vessels, integrating an IEE unit into a cruise vessel presents several architectural and spatial constraints that must be carefully considered to ensure the project's feasibility and operational reliability.

The IEE unit requires dedicated space in close proximity to both the jacket water loop and the mechanical load it will power. This proximity reduces losses and minimises the complexity of piping and shaft alignment. The IEE must be installed on a stable, vibration-tolerant platform, ideally on the engine room floor or in a nearby machinery space, to withstand vibrations and ship motions. While the unit's footprint is typically moderate (approximately the size of a small compressor), additional space must be allocated for thermal insulation, piping, valves, and maintenance access.

Another architectural constraint involves the cooling sink, which is essential for the IEE's thermodynamic cycle. The IEE works by expanding a working fluid from a high temperature (typically around 90 °C from the main engine's jacket water) to a lower temperature (around 84 °C), before transferring that heat to a cooler fluid at 20–26 °C. Without a cooling sink, the temperature gradient would collapse, and the engine would cease to produce mechanical energy. The sink acts like a thermal drain, enabling the cycle to restart continuously.

On ships, this sink is often provided by seawater cooling loops or the vessel's low-temperature circuit. However, the availability of this cooling fluid is not always guaranteed. Consequently, space must be

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allocated for the integration of heat exchangers, piping and flow control units connecting the IEE to this cooling infrastructure. In some cases, additional spatial and energy demands may be incurred by the need for boosting or auxiliary pumps.

6.3.3 Economic assessment

As was done for the fishery and cargo cases, PBT is obtained by considering Scenario 2. The IEE prototype Capex is obtained by multiplying the CAPEX by twenty-five (according to the most feasible scenario). It should be noted that the cost of a larger IEE does not increase linearly, so it is expected that the CAPEX cost will be lower and the economic outlook will be slightly better in the real world.

Table 6.8: IEE economic parameters on Cruise

Parameter	Value	Unit
Capex	20,254	€
Annual Saving	5,107	€/y
Simple PBT	4,0	y

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7 TES analysis

Within the ZHENIT project, the Thermal Energy Storage system (TES) under scope is based on PCM, exploiting latent heat derived from waste heat on board. This technology is intended as a supporting system to other ones, aiming at enhancing energy production and operational flexibility. In the maritime context, TES could enhance the ability of onboard systems to adapt to highly variable conditions. Unlike land-based systems, ship energy systems must operate under non-stationery and mission-dependent conditions, when waste heat is not always available when needed and its temperature and flow rate can vary significantly over time. Moreover, energy demand profiles are often asynchronous with propulsion.

The TES prototype developed in the project is characterized by a compact design (approximately 1 m^3), and a thermal-to-electric equivalent capacity of 3 kWth. The TES should not be interpreted as primary energy generator, but rather as a thermal buffering system that enhances the flexibility of WHR technologies. Regarding economic characteristics, the prototype registers a CAPEX of approximately 34,000 €. However, this cost is not fully representative of an industrial-scale solution. The economic assessment has therefore been conducted based on scalability assumptions rather than on the actual prototype cost. Indeed, the latter refers to a single unit developed for research and demonstration purposes, characterized by specific design requirements related to performance monitoring, including a high level of instrumentation and sensor integration, as well as associated space constraints. These aspects inevitably lead to higher costs compared to those expected for a fully industrialized technology. Additional factors typical of the prototypal phase further contribute to cost overestimation, including the absence of economies of scale, the adoption of tailored construction solutions, non-standardized design and integration processes, and higher costs associated with assembly and experimental validation.

The assessment based on a quantitative approach has been considered, evaluating the nominal capacity of the prototype and the vessel's operational profile. In principle, recoverable energy could be estimated by combining the TES nominal power with the daily discharge hours, the number of sailing days, and a utilization factor that reflects the effective operation of the system. However, the application of this methodology revealed significant limitations. First, the small capacity of the prototype leads to a negligible contribution to the overall onboard energy demand (0-1%), even under optimistic assumptions. Meaningful savings would require a scale-up of the system, which would significantly increase costs, energy demand for charging, and integration constraints onboard. Moreover, the utilization factor represents a major source of uncertainty, as it strongly depends on the frequency of charge/discharge cycles, the availability of waste heat, and the vessel's operational profile. Due to the lack of reliable data or validated dynamic models, this parameter could not be defined with consistency. As a result, a purely quantitative estimation was deemed not sufficiently reliable, and the analysis was complemented with a qualitative assessment focusing on integration potential, operational flexibility, scalability, and techno-economic barriers of the TES system.

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Fishery

Fishery vessels are characterized by highly dynamic and discontinuous operation, alternating phases of navigation, fishing, and idle/stationary conditions, variable auxiliary loads (e.g. refrigeration, winches, onboard processing). As a result, waste heat is intermittent and variable in temperature energy demand is not synchronized with heat availability. This leads to frequent charge/discharge cycles, often multiple times per day.

If properly designed, ORC, SR&D and IEE could cover approximately 5-20% of the on-board electric energy demand, representing a significant but variable contribution to energy savings. TES could limit the intermittency of the heat source, stabilizing the operation during frequent start/stop tasks. However, the limited space available on fishery and the scarce waste heat available compared to energy demand of electrified services make the application of TES with these technologies challenging. TES prototype energy capacity is relatively low; therefore, upsizing would be necessary to achieve higher performance of each technology, consequently increasing costs, lowering economic feasibility.

Cargo

Cargo vessels typically operate under steady-state conditions over long navigation periods, relatively constant engine loads, stable auxiliary power demand. Therefore, waste heat is continuous and predictable energy demand is more closely aligned with heat availability. In this case, TES is less critical for continuity and is mainly useful for handling transient conditions (e.g. maneuvering, slow steaming) smoothing minor fluctuations. Charge/discharge cycles are therefore longer and less frequent.

Unlike in highly dynamic systems, the effectiveness of TES in cargo vessels is further limited by the low frequency of charge–discharge cycles. Since waste heat is continuously available and can be directly utilized, the storage system is only partially exploited, often remaining in a semi-charged state. This results in reduced utilization of the PCM capacity and increased impact of thermal losses over time, ultimately weakening the techno-economic justification of TES integration.

Cruise

Cruise vessels are characterized by larger energy needs since the ship hosts many services not only for the navigation, but also for passengers. However, waste heat is more predictable since navigation routes are defined and travelled at less variable loads. Therefore, the main implication for TES application on cruises should be to satisfy large energy needs by implementing high-capacity technology. Due to the very high and continuous energy demand, small-scale TES units do not provide meaningful benefits in terms of energy supply or operational flexibility. Instead, effective TES integration requires scaling up to hundreds of kWh or even MWh levels, where the storage system can actively contribute to energy management strategies such as peak shaving, load shifting, and optimization of waste heat utilization. In such configurations, high number of modules would increase a lot costs, lowering the economic feasibility of the solution.

Active & Passive WHR Technology Integration

In support of what is mentioned in this Chapter, the scientific publication *“Optimally integrated waste heat recovery through combined emerging thermal technologies: Modelling, Optimisation and Assessment for Onboard Multi-Energy Systems”*, by Pouriya H. Niknam, Robin Fisher, Lorenzo Ciappi and Adriano Sciacovelli[24] must be referenced.

This article provides a detailed assessment of the benefits associated with the integration of TES technologies with the three active waste heat recovery technologies studied in the ZHENIT project (ORC, SR&D, and IEE), and a focused read is recommended.

The study is based on real-life conditions and considers a representative 17-day voyage performed by the AIDAluna cruise ship. This voyage exemplifies the typical operational conditions of cruise vessels, encompassing variable load profiles, multiple port calls and fluctuating waste heat (WH) availability. The cruise ship is equipped with four 9M43C Caterpillar diesel engines, delivering a total electrical capacity of 36 MW.

As the publication highlights, the most significant synergies involving TES occur in combination with high-temperature ORC (HT-ORC) and sorption systems operating at low and medium temperatures. In these configurations, TES supports active technologies by mitigating fluctuations in waste heat availability. This allows for more stable operation and improved utilisation of the recovery systems. Although TES's contribution is inherently intermittent, its impact on the systems is significant.

In terms of demand coverage, TES indirectly contributes by supporting active technologies, accounting for up to 35% of the thermal energy supplied to WHR units. It also directly covers some of the onboard heat demand. This supporting role increases the availability of recoverable waste heat and improves the ability of active technologies to meet electrical, cooling, and mechanical demands. ORC and sorption technologies in particular achieve substantial coverage of onboard demand, supplying around 30% of the electrical demand and 50% of the cooling demand respectively.

Finally, while the benefit of the IEE is relatively minor compared to the other two technologies, its combination with TES is particularly well suited to the utilisation of low/medium-temperature waste heat.

In conclusion, as mentioned in this deliverable and highlighted in the aforementioned publication, TES emerges as a key enabler rather than a primary recovery technology, with its primary function in improve system integration.

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[24] Pouriya H. Niknam, Robin Fisher, Lorenzo Ciappi, Adriano Sciacovelli, Optimally integrated waste heat recovery through combined emerging thermal technologies: Modelling, optimization and assessment for onboard multi-energy systems, Applied Energy, Volume 366, 2024, https://doi.org/10.1016/j.apenergy.2024.123298.

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8 Replicability potential evaluation

To evaluate the replicability potential of the waste heat recovery technologies proposed in the ZHENIT Project, a replicability matrix approach has been adopted.

The replicability potential has been assessed using a combination of technical and economic criteria. From a qualitative point of view, technical scalability reflects the capability of the technology to be implemented across different vessels and operational scales, according to the architectural constraints mentioned in previous chapters. Economic feasibility is evaluated based on the expected payback time of the previously evaluated solution.

The definitions of the technical and economic feasibility scores are given in Table 8.1 and Table 8.2, respectively.

Table 8.1: Definition of technical feasibility

Technical Feasibility	Description
Very Low (VL)	Integration faces critical constraints (space, interfaces, power demand, safety) that require highly customized solutions.
Low (L)	Some non-negligible constraints exist, requiring tailored adjustments to ensure operability.
Medium (M)	The technology is compatible with standard ship environments, with constraints that can be managed through routine engineering solutions.
High (H)	Constraints (space, power, interfaces, operational profiles) are minimal or negligible, enabling straightforward integration.

Table 8.2: Definition of economic feasibility

Economic Feasibility	Description
Very Low (VL)	The payback time is too long compared to typical ship lifecycles or operational budgets.
Low (L)	The payback time is relatively long and acceptable only in specific operational conditions.
Medium (M)	The payback time is reasonable and meets standard ship investment expectations.
High (H)	The payback time is short and highly attractive for shipowners.

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The scores for technical and economic feasibility are combined using the replicability potential matrix presented in Table 8.3, which categorises replicability as ranging from “very low” to “high”. A dedicated replicability matrix has therefore been developed for each technology, highlighting the most suitable waste heat recovery system for each kind of vessel.

Table 8.3 Criteria for replicability potential

Replicability potential		Technical Feasibility			
		Very Low (VL)	**Low (L)**	**Medium (M)**	**High (H)**
Economic Feasibility	**Very Low (VL)**	Very Low (VL)	Very Low (VL)	Low (L)	Low (L)
	Low (L)	Very Low (VL)	Low (L)	Low (L)	Medium (M)
	Medium (M)	Low (L)	Low (L)	Medium (M)	Medium (M)
	High (H)	Low (L)	Medium (M)	Medium (M)	High (H)

8.1 ORC Replication matrix

The potential for replicability of ORC technology in three different vessel types is outlined in Table 8.4.

From a technical perspective, feasibility varies according to the structural layout and size of the vessel. This score is low for fishery vessels, which are typically small, have limited available space, and are lightweight, meaning that additional mass can significantly affect trim and stability. Technical feasibility is considered as medium for cargo and cruise ships, which could offer larger volumes, a more constant heat source and more robust structure.

Indeed, from an economic perspective, the feasibility of this solution is considered very low for all three types of vessels. The high cost of the technology and the limited energy savings mean that this solution is not currently economically viable.

In conclusion, the replicability level of this technology in the marine sector is assessed as very low for fishery vessels and low for cargo and cruise ships.

Table 8.4 Replicability Matrix – ORC Solution

Replicability potential	Technical Feasibility	Economic Feasibility	Replicability level
Fishery	Low (L)	Very Low (VL)	**Very Low (VL)**
Cargo	High (H)	Very Low (VL)	**Low (L)**
Cruise	Medium (M)	Very Low (VL)	**Low (L)**

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8.2 SR&D Replication matrix

The potential for replicability of SR&D technology in three different vessel types is outlined in Table 8.5.

For the aforementioned reasons relating to structure and heat availability, the technical feasibility is medium for fishery and cruise vessels, and high for the cargo vessel.

From an economic perspective, the feasibility of this solution can be considered low for cruise vessels, due to the high PBT, but medium for fishery and cargo vessels, since the prototype can very efficiently meet the vessel's cooling and freshwater needs.

In conclusion, the replicability level of this technology in the marine sector is assessed as low for cruise vessels and medium for cargo and fishery ships.

Table 8.5 Replicability Matrix – SR&D Solution

Replicability potential	Technical Feasibility	Economic Feasibility	Replicability level
Fishery	Medium (M)	Medium (M)	Medium (M)
Cargo	High (H)	Low (L)	Medium (M)
Cruise	Medium (M)	Low (L)	Low (L)

8.3 IEE Replication matrix

The potential for replicability of IEE technology in three different vessel types is outlined in Table 8.6.

For the aforementioned reasons relating to structure and heat availability, technical feasibility is low for fishery vessels and medium for cargo and cruise ships.

Indeed, from an economic perspective, the feasibility of this solution can be considered high for all three types of vessels. The low cost of the technology and the considerable energy savings mean that this solution is currently economically viable.

In conclusion, the replicability level of this technology in the marine sector is assessed as low for fishery vessels and medium for cargo and cruise ships.

Table 8.6 Replicability Matrix – IEE Solution

Replicability potential	Technical Feasibility	Economic Feasibility	Replicability level
Fishery	Very Low (VL)	High (H)	Low (L)
Cargo	Medium (M)	High (H)	Medium (M)
Cruise	Medium (M)	High (H)	Medium (M)

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8.4 TES Replicability potential

As the TES technology acts as a storage system powered by waste heat rather than generating energy, its replication potential could be very high from a theoretical point of view, since waste heat is always generated during a vessel's trip and can easily be converted into useful energy by the previously explained technology.

Nevertheless, from a technical point of view, the techno-economic feasibility, and as a consequence the replicability potential, is strongly affected by two main constrains:

- Poor synchronisation between heat availability and vessel energy demand. For example, during navigation, heat from storage systems may not be necessary, since waste heat is widely available and can be converted directly into useful energy, such as electricity or cooling. When the vessel is stopped in port, the energy demand may be considerable, but the amount of waste heat is limited. This results in the rapid discharge of previously stored waste heat into the TES system.
- A scaled-up TES capable of storing a significant amount of thermal energy, enough to meaningfully improve a vessel's efficiency, would require substantial physical space. Such a large system would be difficult to accommodate within the already highly optimised and space-constrained engine rooms. Furthermore, the increased mass of a larger TES could have a significant impact on the vessel's weight distribution, potentially increasing the energy required for propulsion.

Table 8.7 summaries the information previously mentioned, categorised by vessel typology.

Table 8.7: Replicability Matrix – TES Solution

TES role	Vessel	Techno-economic feasibility	Replicability level
Provide thermal energy to auxiliary equipment for electricity generation or cooling, reducing fuel consumption and improving overall vessel energy efficiency.	Fishery	Low: a match between charge and discharge cycles exists, but the cost makes the solution unattractive.	Low (L)
	Cargo	Low: poor synchronisation between heat availability and vessel's energy demand. In addition, the solution would need to be scaled up, increasing required space and vessel weight. The high costs further reduce its attractiveness.	Low (L)
	Cruise	Low: poor synchronisation between heat availability and the vessel's energy demand. The solution would require a massive scale-up, increasing the required space and the overall vessel weight. The high costs further reduce its attractiveness.	Low (L)

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From an economic point of view, scaling up the TES to a size capable of delivering tangible benefits for the different vessel types makes the solution poorly economically feasible, given the unit cost of more than €11,000 per kW.

For these reasons, the current replicability potential can be assessed as low for all vessel categories. Nevertheless, due to the interesting nature of the solution and its potential benefits, future cost reductions and technological improvements could increase the relevance and applicability of this technology. In any case, implementing a TES unit will require precise design and consideration of multiple variables, such as engine load profiles, vessel energy balances at different operational configurations and available onboard space, as well as hydrodynamic simulations.

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9 Conclusions and recommendations

Deliverable 5.3, titled "Scale-up and Replication Feasibility Studies", assessed the feasibility of replicating the four WHR solutions deployed under the ZHENIT project on the three pilot vessels. To achieve this, the energy savings, architectural constraints and economic benefits were evaluated at both the prototype level and for a scaled-up version that better matched the needs of the vessel. The main conclusions and recommendations for each configuration are summarised below.

Specifically for **Organic Rankine Cycle (ORC) technology**, the replicability level in the marine sector is assessed as very low for fishery vessels and low for cargo and cruise ships. This is primarily due to significant architectural constraints and low economic feasibility, given the current high cost of the technology and limited energy savings. The main constraints and recommendations to be taken into consideration when approaching this technology are as follows:

- The limited space and complex layout of engine rooms could make the installation of the ORC complicated and potentially increase the complexity of maintenance operations;
- The installation of additional weight requires structural and stability verification;
- Integration with existing exhaust ducts, cooling loops and automation systems can be challenging; and
- Exhaust gas should be carefully managed, ensuring that backpressure remains within acceptable limits and that exhaust temperatures stay above the dew point to prevent condensation and corrosion.

For Sorption **Refrigeration and Desalination (SR&D)** technology, the replicability level is assessed as medium for fishery and cargo vessels and low for cruise ships. This is due to a combination of prominent performance results, and economic and architectural limitations, which must always be considered when implementing new technology on board. Economic savings represent the primary driver justifying the investment, which has to be critically assessed for complex cases such as the cruise one. The main constraints and recommendations are similar to those previously presented for the ORC, and in particular, when approaching this technology, it is important to consider that:

- the limited space and complex layout of engine rooms could make installing the unit and its auxiliaries complicated, potentially increasing the complexity of maintenance operations;
- The need for proximity to heat sources and cooling sinks;
- the need for stable waste heat availability for optimal unit operation and efficiency;
- Structural and stability verification due to the increase in vessel weight.

Funded by the European Union

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Regarding the **Isobaric Expansion Engine (IEE)** technology, the replicability level is assessed as low for fishery vessels and medium for cargo and cruise ships. This is the combination of architectural constraints, which, as always, have a significant impact, as well as economic savings. The low cost of technology and the considerable energy savings mean that this solution is currently economically viable. The main constraints and recommendations to be taken into consideration when approaching this technology are:

- Engine-room space limitations, and complex integration within existing ship systems;
- Need for a stable and vibration-tolerant mounting platform, to avoid misalignment, structural fatigue, or noise during vessel operation;
- Low-temperature heat availability from the jacket-water circuit, which limits the thermodynamic efficiency of the cycle; and

Finally, the last technology evaluated was the **Thermal Energy Storage (TES)**, which was assessed from a qualitative point of view. While the replicability potential of TES technology is theoretically high, its deployment in real environment is strongly limited by two major technical constraints.

Firstly, there is a poor match between heat availability and onboard energy demand. Secondly, in order to deliver tangible energy benefits, a TES would require considerable space and add significant mass to the vessel. This would be difficult to accommodate within the highly confined layouts of engine rooms and could affect vessel stability and propulsion efficiency. The technology is also penalised economically by very high specific costs (above €11,000/kW), making large-scale installations unattractive in the current market.

For these reasons, the replicability potential of TES technology across fishery, cargo and cruise vessels is currently assessed as low. Future cost reductions and technological improvements could enhance its viability.

In conclusion, this report highlights the scale-up and replicability potential of the technology deployed under the ZHENIT EU project. However, it is important to consider that each vessel is unique, and detailed designs and energy balances must be conducted to ensure a good match and the achievable benefits of installing these technologies onboard.

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