

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



D 2.5 | Collection of guidelines for future scaling up of technologies for onboard integration

WP2 – Modelling and Design WH valorisation solutions at different temperatures

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

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Abbreviation and Acronyms

Acronym	Description
CP	Calorific Power
EER	Energy Efficiency Ratio
IMO	International Maritime Organization
ORC	Organic Rankine Cycle
TRL	Technology Readiness Level
HFO	Heavy Fuel Oil

Executive Summary

The ZHENIT project aims at developing and validating some innovative technologies for waste heat valorization on board of vessels (i.e. adsorption chiller and desalination unit, ORC – heat pump with ejector, Isobaric Engine) and to support the main engine through innovative sails (i.e. rigid sails). Specifically, the proposed technologies for waste heat valorization are still at low TRL, ranging from TRL 4 up to TRL 5, while the innovative eSails are closer to a real marketability. Accordingly, at this stage it is important to define some preliminary guidelines for upscaling of these technologies in order to guide the future design efforts towards the future commercialization.

At this stage, only energy efficiency and power density are considered, since techno-economic analyses will be provided by the end of the project. In order to evaluate the efficiency aspects, the simplified integration analysis on board of three reference vessels, namely, a large ferry ship, a cargo vessel, and a large fishing vessel was performed. This analysis mainly aimed at evaluating the impact of the integration of the technologies on board, with a focus on the possible fuel saving achievable by the different scenarios. This exercise considered, on one hand, the available waste heat on board of the reference vessels and the possible demands, in terms of heating, cooling, power and desalinated water. On the other hand, possible space constraints on board were analyzed. The starting point for each of the ZHENIT solutions was the energy efficiency and the power density evaluated either experimentally or numerically during the first phase of the project. The power density was only considered for the adsorption machine, being the one closer to a commercial level.

The obtained data demonstrated that the ZHENIT solutions can be extremely attractive in application where the space available on board of the vessels does not represent a critical barrier. This is especially valid for large vessels, such as ferries, cruises and cargos. Moreover, in case of newly built vessels, the possibility of analyzing the integration on board since the designing phase could make this aspect easy to overcome. In vessels having these features, relevant fuel savings up to 7% of the overall consumption on board can be achieved. On the other hand, cases where the space constraints become critical, like the fishing vessels, are less attractive for the ZHENIT integration.

Based on the above mentioned results, preliminary guidelines for upscaling foresee the further increase of the energy efficiency of each technology of at least 20% compared to the current development level. Moreover, a power density of 20 kW/m³ could be considered as a relevant target to meet. Similarly, a reduction the footprint of the eSails could be useful to increase the number of sails that can be installed in each vessel.

1 Introduction

The aim of this deliverable is to identify the targets to be achieved by each ZHENIT technologies, while upscaled, in order to be considered suitable for real integration on board of vessels. These targets primarily address energy efficiency aspects and power density. Economic analysis will be investigated in WP5.

To define these guidelines, at first the current best match between the ZHENIT technologies under development and the waste heat availability on board of reference vessels is reported. The expected energy savings thanks to the integration of the different technologies on board are evaluated.

Starting from the reported analysis and the constraints for realistic integration on board, some preliminary guidelines to increase the energy efficiency as well as the power density for each technology are provided. These shall be taken into account by each technology manufacturer in the future design of the technologies targeting their commercialization.

2 Summary of the specific performance indicators of the ZHENIT technologies

The detailed description of the operation and main features of the core ZHENIT technologies can be found in the deliverables presented after the development stage in WP2. More specifically, D2.1 for the adsorption chiller and desalination unit, D2.2 for the Isobaric Engine, and D2.3 for the ORC-heat pump with ejector. Beside the three waste heat-driven technologies, also the role of the integration of the eSail on board is investigated in this analysis. A detailed description of the main features of this technology can be found in D1.2.

Since the aim of this deliverable is the definition of guidelines for future upscaling of these technologies once ready for the commercialization, the analysis provided here starts from the typical operating conditions expected and the current performance figures that have been either experimentally or numerically evaluated for each technology. Actually, due to the delay of prototypes manufacturing and experimental characterization, at this stage most of the reported performance refers to the numerical investigation. Nevertheless, these are only considered as basis for the investigation and can be easily updated with experimental data when necessary.

Table 1 summarizes the starting point employed for the reported analysis. It is important to highlight that, for the adsorption unit, being the waste heat-driven ZHENIT technology closest to the market, a reliable estimation of the current volumetric power density was performed. Differently, for the cases of Isobaric Engine and ORC and heat pump with ejector, since they are still in a lab scale prototyping phase, it looks more reasonable to consider only energy efficiency parameters, since the design efforts for an engineered system will be part of future developments. Regarding the eSail, a specific version currently manufactured by Bound4Blue was considered as reference, in which the expected fuel saving as well as the footprint for its installation on board are considered as reference parameters for the investigation.

Table 1: Reference data considered for the performed analysis.

Technology	Waste heat source	Provided service	Current reference performance figures
Adsorption chiller and desalination	Cooling circuit of the engine: $T < 80$ °C	Cold water for space cooling down to 7 °C	Thermal EER_cool (cooling energy per unit of waste heat) = 0.4

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		Desalinated sea water	Thermal EER _{des} (desalinated energy per unit of waste heat) = 0.6 Specific power = 15 kW/m ³
Isobaric Engine	Cooling circuit of the engine: T < 70 °C	Mechanical energy or electricity	Isobaric Engine efficiency (mechanical power per unit of waste heat) = 0.05
ORC-heat pump with ejector	Exhaust gases from the engine: T > 120 °C	Electric power (ORC) Heating and/or cooling (heat pump)	ORC efficiency (electric power per unit of waste heat) = 0.08
eSail	-	Dragging force to support the vessel' sailing	Fuel saving per year current eSail model 2 (26x4.5)= 197 tonne/y Fuel saving per year current eSail model 2 (22x4.5)= 120 tonne/y Fuel saving per year current eSail model 2 (18x4.5)= 87 tonne/y Technology footprint: 45 m ²

3 Definition of reference use cases

In the following sections, the identified referene use cases are briefly described. They will be the same replication vessels which will be considered for the analysis performed in WP5 for the environmental and economic assessment of ZHENIT solutions on board of different vessels.

3.1 Ferry ship

3.1.1 General description

The Elyros is a Ro-Ro ferry vessel managed by Attica, sailing between Athens and Crete. Figure 1 and Annex I report a picture of the vessel and the original drawings of the thruster installed on board of the vessel.



Figure 1: Photo of the Elyros vessel.

Elyros length is 192 m with a tonnage of 33635 tons and passenger capacity of 1880 people. It is equipped with two large main diesel engines, with total power of 8400 kW, and diesel generators both for navigation and port, with total power of 3900 kW. Air conditioning energy consumption is estimated in 800 kW in summer and 200 kW in spring during the sailing phase. Currently, it is covered by 6 screw compressors of 200 kW each, using R407 as refrigerant.

3.2 Cargo ship

3.2.1 General description

The MV Ankie is a general cargo vessel operated by Van Dam Shipping. It operates in the spot market in Europe. Principal dimensions are listed in Table 2. The general arrangement is included in Annex I and a picture of the sailing vessel is reported in Figure 2.

Table 2: Principle particulars MV Ankie.

Lpp	84.9	m
B	12.5	m
T	5.3	m
Speed (max)	13	kn
Displacement	3636	ton
IMO number	9331359	
Propulsion	1x CPP propeller, bow thruster	
Main engine	Wartsila 9L20, 1000rpm, 1800kW	
Auxiliary engine	210 kVa, 400V, 50Hz	
Shaft generator	Stamford HC.M534C2, 390 kVa, 1500 rpm, 400/231V 50Hz, PF=0.8	



Figure 2: Photo of the MV Ankie.



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The ship has a single diesel engine, connected through a gearbox and power take-off (PTO) to a controllable pitch propeller. A schematic of the single line diagram is shown in Figure 3. The emergency generator is normally not used. In harbour operations the Auxiliary generator is used. Shore power is only used in dry dock. During sailing the shaft generator is used to provide electric power. The auxiliary generator is then shut down. When the bow thruster must be used, the shaft generator is decoupled from the main switchboard and coupled directly to the bow thruster. The auxiliary generator provides then the power to the main switchboard. This is done to avoid frequency fluctuations on the main grid when the bow thruster accelerates. The ship sails with constant RPM. Propeller pitch is used to set the desired speed.

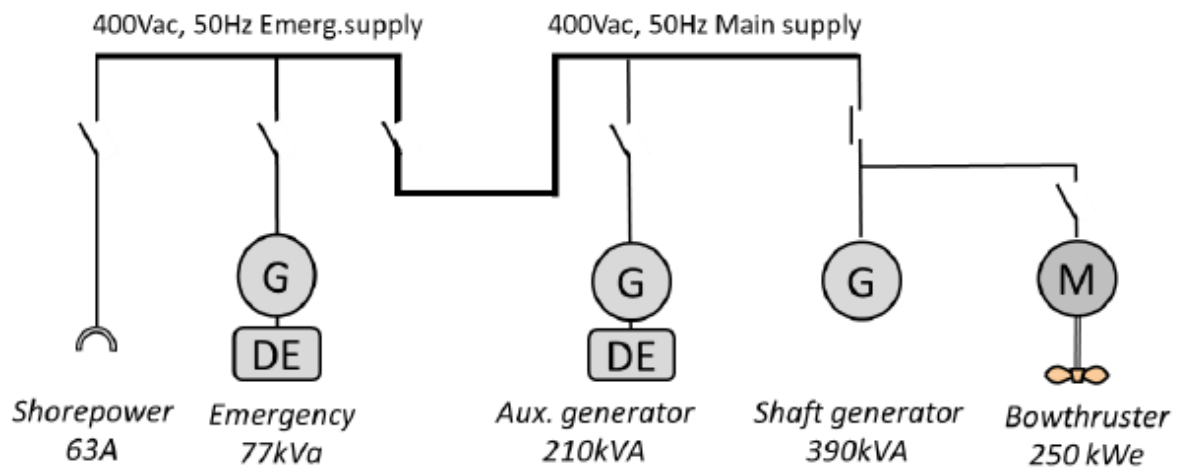


Figure 3: Schematic single line diagram of the MV Ankie.

3.3 Large fishing vessel ship

3.3.1 General description



Figure 4: Photo of the Giacomo Giacalone Primo.

The Giacomo Giacalone Primo (Figure 4) is a fishing vessel belonging to the Mazara del Vallo, Sicily, fleet, primarily engaged in shrimp trawling. It is one of approximately 80 vessels in the fleet, all of which share similar characteristics. These include an overall length ranging from 25 to 30 meters, a beam of less than 10 meters, a tonnage of around 150 tons, and the presence of onboard facilities such as processing and refrigeration units, as well as hydraulic-powered fishing equipment.

A typical mission involves remaining in fishing areas for up to 30 days, with each fishing cycle lasting about five hours, followed by a phase of catch storage and relocation to a new fishing site. The onboard power generation system features a main heat engine for propulsion, supported by two auxiliary generators that supply power to the onboard utilities and fishing equipment. Key systems include the catch processing and refrigeration units (40 kW), hydraulic systems for handling the fishing gear, and utilities for the crew, such as galleys, air conditioning on the bridge, and navigation systems.

A diagram of the main elements that contribute to the ship's energy balance is provided below in Figure 5. Also additional information about the water tank and the fuel tank are provided in order to define the overall requirement of the ship.

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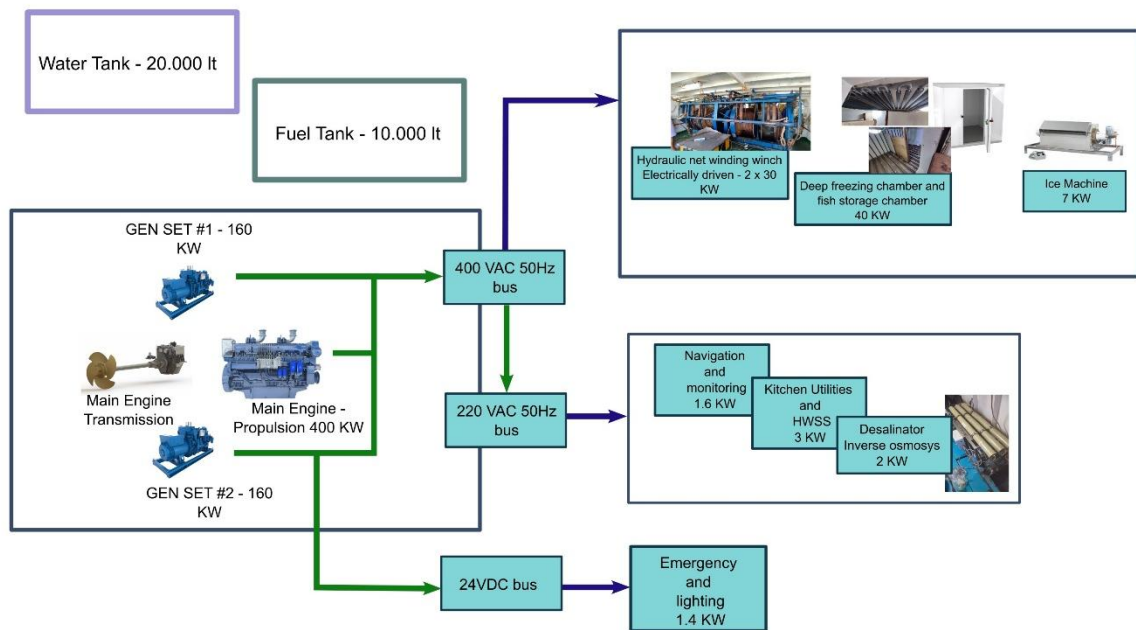


Figure 5: Diagram of the systems on board of the Giacomo Giacalone Primo.

The typical mission profile includes a sea voyage lasting approximately 30 days, during which the ship must operate entirely autonomously with regard to key services, such as crew sustenance and storage of the catch. The payload, consisting of shrimp, is initially blast-frozen in a rapid freezing chamber (-30°C, approximately 3 m³ in size), and then stored in cold rooms at -18°C located within the ship's hull (estimated capacity: 40 m³). The catch is further preserved by ice flakes, produced directly on board by a dedicated machine. This machine utilizes a water supply of about 20,000 liters, non-potable, which is continuously replenished through a reverse osmosis desalination system producing around 80 liters/h.

The fleet's vessels are all constructed from naval-grade steel, with an average age of around 25 years. Despite the advanced age of the fleet, shipowners have progressively invested in downsizing the engines—spurred by EU policies and rising fuel costs—resulting in significant reductions in overall fuel consumption and a reduction in propulsion system weight by approximately 1,000 kg. These changes were partially driven by the improved efficiency of newer marine engines, as well as the understanding that slow steaming during transit does not negatively impact overall productivity.

This downsizing has also created additional space in the engine room. The engine rooms of inspected vessels offer considerable free space, estimated at 2-3 m³ near the propulsion unit. These circumstances

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make this type of vessel particularly suitable for retrofitting with WH-to-X technologies, provided that the most appropriate technology for supplying onboard utilities—or replacing existing systems with new equipment that utilizes waste heat—is identified.

An additional point of interest is the vessel’s motor propulsion system and power supply for essential services. Two identical generator sets (required by law to ensure redundancy) operate alternately to balance usage and maintenance.

All systems must be certified by the classification society and comply with RINA regulations. Regarding redundancy, the only duplicated systems are the generator sets and the electro-hydraulic systems used for handling fishing nets.

4 Analysis of the integration routes

In this section, the analysis of the possible ZHENIT technologies integration routes on board of the reference vessels is reported, as baseline for the definition of the guidelines for technologies upscaling.

4.1 Possible ZHENIT integration routes on board of the reference vessels

4.1.1 Ferry ship

4.1.1.1 Adsorption chiller

According to data provided by the owner, during navigation, the Elyros main engines (two) are operated at 30% of the available power, for a total of 8400 kW of generated power ($P_{engine} = 8400 \text{ kW}$). Since no data acquisition on the waste heat available for the cooling of the main engine is available, it is estimated equal to 30% of available generated power, ($\dot{Q}_{wasted} = 2520 \text{ kW}$). Assuming that the EER (Energy Efficiency Ratio) of the adsorption machine is equal to 0.4, as reported in Table 1, ($EER_{ads} = 0.4$), the theoretically cooling power that can be generated on board by the adsorption chiller, calculated using [$P_{cooling_th} = \dot{Q}_{wasted} * EER_{ads}$], is equal to 1008 kW:

$$P_{cooling_th} = \dot{Q}_{wasted} * EER_{ads} \quad [\text{Eq.1}]$$

Elyros cruise ship requests 800 kW ($\dot{Q}_{c-requested} = 800 \text{ kW}$) of cooling power during sailing, therefore the cooling power that can be generated by the adsorption units is sufficient to satisfy the cooling demand, as summarized in Figure 6.

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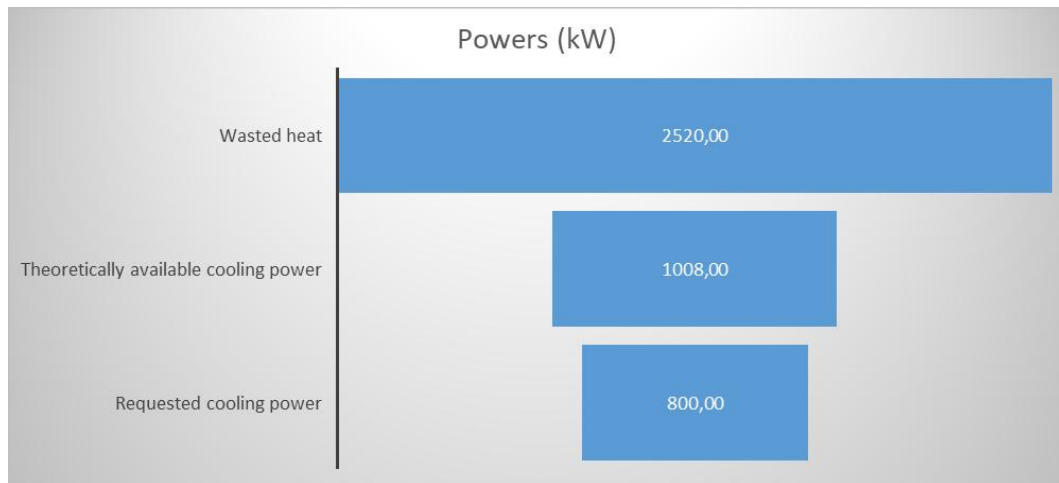


Figure 6: Wasted heat available from the main engines during sailing, theoretically available cooling power and requested cooling power

The following Table 3 shows the technical characteristics of the adsorption machine considered for the analysis.

Table 3: Adsorption chiller main characteristics.

Adsorption chiller parameter	Value
Single module Adsorption chiller weight	200 kg
Single module Adsorption chiller volume	2 m ³
Single module adsorption chiller power	30 kW
Adsorption chiller power/volume ratio	15 kW/m ³
Adsorption chiller power/weight ratio	0.15 kW/kg

To satisfy entirely the cooling demand, considering the adsorption chiller characteristics, it is then necessary to install 27 modules.

Starting from the assumptions above reported, an energy analysis of the impact of the integration of the adsorption chiller on board was performed. The following assumptions were used in the calculation:

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- 8 hours of sailing time ($t_{sailing} = 8 \text{ h}$);
- Main engine efficiency, set to $\eta_{engine} = 0.45$;
- Average calorific power for HFO (Heavy Fuel Oil) of $CP_{HFO} = 42.7 \text{ MJ/kg}$;

The energy and fuel consumption have been estimated using the following equations:

$$E_{cons} = \frac{P_{engine} * t_{sailing}}{\eta_{engine}} \quad [\text{Eq.2}]$$

$$Fuel = \frac{E_{cons} * 3.6}{CP_{HFO}} \quad [\text{Eq.3}]$$

The same calculation can be performed considering the engine used for the auxiliaries, which is used mainly to produce electricity for the on board auxiliaries (e.g. chillers, ventilation system, water pumps, etc.).

The obtained results are summarized in Table 4.

Table 4: Summary of the results concerning energy and fuel consumption of the main engine and the engine used for auxiliaries.

Main parameters concerning fuel consumption	Value
Energy consumption (main engine)	149333.3 kWh
Fuel consumption (main engine)	12590.16 kg
Energy consumption (auxiliaries engine)	51000 kWh
Fuel consumption (auxiliaries engine)	4299.77 kg

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To calculate the energy consumption related to the air conditioning on board of the vessel, it was considered a reference vapour compression chiller with an EER equal to 2.5, which means that to guarantee the satisfaction of the cooling load, the power absorbed by the auxiliary generator is equal to 320 kW according to the following equation.

$$P_{cooling_el} = \dot{Q}_{c-requested} / EER_{elect} \quad [Eq.4]$$

Taking into account what is above reported, if the necessary cooling power is generated by the adsorption machine, it follows that the power developed by the auxiliary engine can be decreased accordingly to a value equal to 2230 kW. It is therefore possible to calculate the energy consumption of the auxiliary engine when the adsorption chiller is installed on board, calculated according to the following equation, considering the efficiency of the engine for auxiliaries equal to 0.4 ($\eta_{aux\ engine} = 0.4$)

$$E_{cons-aux} = \frac{(P_{aux} - P_{cooling_el}) * t_{sailing}}{\eta_{aux\ engine}} \quad [Eq.5]$$

Using [Eq.3] is possible to calculate the fuel consumption of the engine used to drive the auxiliaries if the cooling demand is completely satisfied by the adsorption chiller, which is 3,760.19 kg. It is then possible to calculate the percentage of estimated fuel saved as the ratio between the estimated fuel consumption of engine for auxiliary after and before the installation of adsorption chiller, which amounts to 12.55 %. The obtained results for the adsorption chiller integration on board of Elyros is depicted in Figure 7.

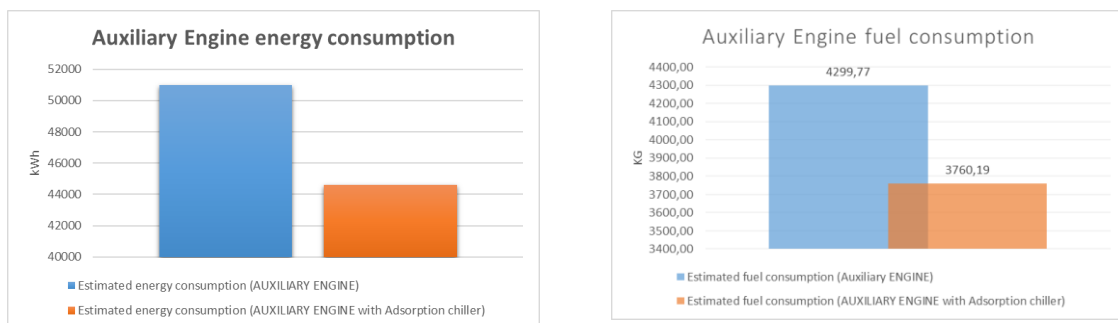


Figure 7: Comparison between energy and fuel consumption of engine used to actuate the auxiliaries in case of installation of adsorption chiller.

The adsorption chiller, alone, is able to save more than 530 kg of HFO. It is important to note that the presence of the adsorption chiller affects only the consumption of the engine for the auxiliaries and not the consumption of the main engine, since the electrical energy is not produced by the latter.

4.1.1.2 ORC

A similar approach as the one described for the adsorption chiller analysis is performed for the ORC integration.

To power the ORC system, it is assumed that the waste heat is taken from the exhaust gases instead than the cooling circuit of the main engine. This is needed by the fact that the ORC requires much higher driving temperature to be operated efficiently. Assuming that approximately 30% of the available power is dissipated through the exhaust gases and assuming that only 30% of the heat contained in them can be recovered, a theoretical power of over 756 kW is available during sailing. From the data reported in Table 1, it appears that the average efficiency of the ORC system under the expected operating conditions equals to 8%, it follows that the ORC system could develop more than 60 kW of electrical power.

$$P_{ORC} = P_{engine} * 0.3 * 0.3 * 0.08 \quad [Eq. 6]$$

Subtracting these additional 60 kW from those saved by using the adsorption machine, it is possible to further reduce the power required by engine used for auxiliaries. The amount of HFO that can be saved if the adsorption machine and the ORC system were installed at the same time is approximately 640 kg, resulting in a fuel saving of almost 15% (see Figure 8 and Table 5).

4.1.1.3 Isobaric Engine

To calculate the theoretically available power guaranteed by the installation of the Isobaric Engine, we assumed to use the portion of waste thermal energy that is not used to operate the adsorption machine. From the previous paragraphs, it appears that by exploiting the over 2.5 MW of available thermal power, it is possible to generate over one MW of cooling power. This value greatly exceeds the ship's cooling requirement, which is equal to 800 kW. It follows that it is possible to exploit part of the waste heat to also operate the Isobaric Engine, while ensuring that the cooling load is met. If we assume that 200 kW of the 2.5 MW available are used, there would be enough thermal power to produce, with the same adsorption chiller, a cooling power greater than 900 kW, therefore largely sufficient to meet the ship's needs during navigation. Based on this reasoning, it was assumed that the Isobaric Engine would be powered with 200 kW of heat coming from the main engine's cooling circuit. The result, assuming an

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Isobaric Engine efficiency of 5% (see Table 1), is that an additional 10.4 kW of electrical power can be developed, which can help further reduce the engine's HFO consumption for auxiliaries.

Repeating the same reasoning already carried out in the previous cases, it is possible to calculate the saving, in terms of kilograms of HFO, which in this case exceeds the figure of 650 kilograms. It follows that the fuel consumption, if all the technologies, namely, the adsorption machine, the ORC system, and the Isobaric Engine were installed at the same time, is reduced of more than 15%, as resumed in Table 5 and Figure 8.

Table 5: Potential fuel saving considering different scenarios.

	Saved fuel (kg)	% on Fuel consumption of Engine for auxiliaries
Adsorption chiller ONLY	539.98	12.55
Adsorption chiller + ORC	641.56	14.92
Adsorption chiller + ORC + Isobaric Engine	659.10	15.33

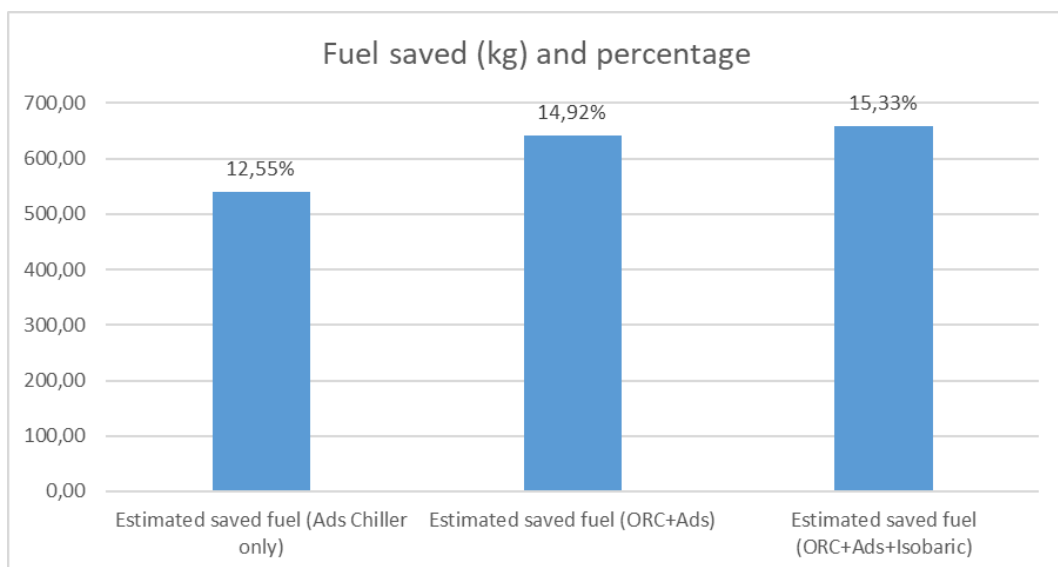


Figure 8: Potential fuel saving considering different scenarios.

4.1.1.4 eSails

To calculate the energy savings that can be obtained by installing the eSails, reference was made to the data provided by the manufacturer as reported in Table 1, which were obtained through an experimental acquisition campaign carried out as part of a previous European project, where the potential energy savings for the different eSails configurations were summarized. These two eSail models were chosen in relation to the size of the vessel Elyros. For the specific case, the installation of 3 eSails (26x4.5) was considered.

The estimation of fuel saving was performed using the following equation:

$$eSail \text{ fuel saving} = \frac{\text{Potential fuel saving} * \text{number of eSail}}{8760} * \text{sailing time} * 1000 \quad [\text{Eq.7}]$$

The fuel saving obtained using the eSail was summed to the fuel saving obtained installing the adsorption chiller, the ORC and the Isobaric Engine, already calculated in the previous sections. The percentage of fuel saving was calculated considering the following equation:

$$\% \text{ of fuel saved} = \frac{eSail \text{ fuel saving} + \text{Fuel saving}_x}{\text{Estimated fuel consumption (Main engine)} + \text{Estimated fuel consumption (Aux)}} \quad [\text{Eq. 8}]$$

Where *Fuel saving_x* is the fuel saved using the different technologies (Adsorption chiller ONLY, Adsorption chiller+ORC, etc). The achieved results are summarized in Table 6.

Table 6: Fuel saving combining the different technologies (eSail 26x4.5)

	Saved fuel (kg)	% on Fuel consumption of the main engines
eSail + Adsorption chiller ONLY	1,079.30	6.39
eSail + Adsorption chiller + ORC	1,181.28	6.99
eSail + Adsorption chiller + ORC + Isobaric Engine	1,198.82	7.10

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In this case, the installation of the eSails affects the energy consumption of the main engine while the other technologies influence the consumption of the engine used to operate all the on-board services as we have seen in the previous sections. So, for a fair comparison, in this case the fuel saving percentage is calculated over the fuel consumption of the main engine. Table 6 summarizes the results of the calculations performed assuming the different scenarios, i.e. eSail plus adsorption machine, eSail plus adsorption machines and ORC system, and finally also adding the Isobaric Engine. In the best case, the fuel savings that can be achieved are almost equal to 1.2 tons of HFO, which corresponds to a reduction in energy consumption of over 7%. The same values can be visualized in Figure 9.

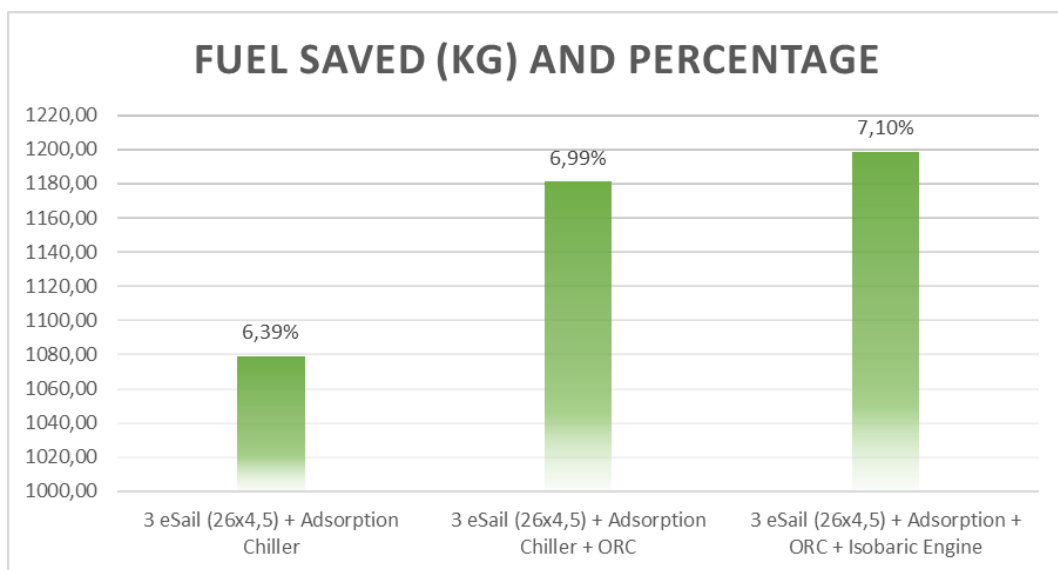


Figure 9: Fuel saving obtained combining the eSails (26x4.5) with the other technologies.

A further analysis was performed to investigate the effect of installing eSails of smaller dimensions 22 m height by 4.5 m in diameter, obviously in this case the energy savings that can be achieved are lower, in fact they do not exceed 6.5% in the best conditions, that is when it is possible to simultaneously install the eSails, the adsorption machine, the ORC system and the Isobaric Engine: the amount of fuel saved in this case is equal to approximately 1,070 kilograms, as shown in Table 7 and Figure 10.

Table 7: Fuel saving combining the different technologies (eSail 22x4.5)

	Saved fuel (kg)	% on Fuel consumption of Engine for auxiliaries

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eSail + Adsorption chiller ONLY	950.54	5.63
eSail + Adsorption chiller + ORC	1052.52	6.23
eSail + Adsorption chiller + ORC + Isobaric Engine	1070.05	6.34

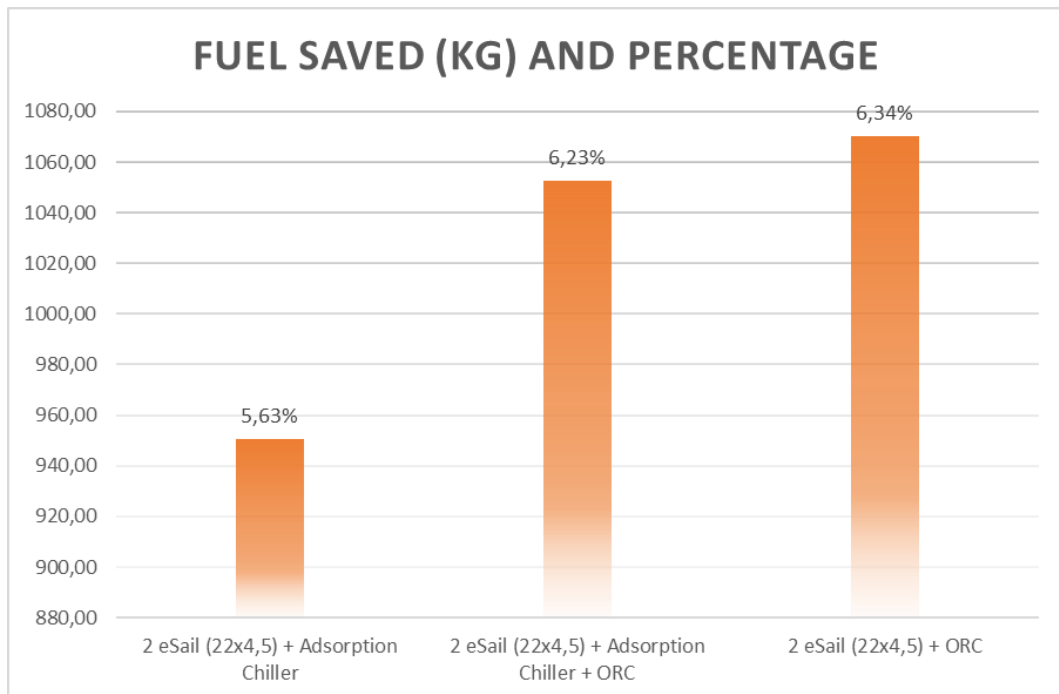


Figure 10: Fuel saving obtained combining the eSails (22x4.5) with the other technologies.

4.1.2 Cargo ship

To perform the analysis, some of the reported data were retrieved from an acquisition campaign aimed at evaluating the effectiveness of installing an eSail on board the vessel. In particular, they were used to define the working profile of the Enkye motor vessel. The operational profile of the propulsion, auxiliary and payload of the 3600dwt general cargo coaster MV Ankie has been determined based on a 1-month monitoring period in spring 2023. The vessel transported cargo in this period between the Netherlands,

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Poland, Estland and Finland. Based on GPS location, propulsion power and auxiliary generator output four operational tasks were identified: 'transit at sea', 'transit in narrow waters', 'loading/unloading' and 'waiting'. Approximately 50% of the time the vessel was in transit. 35% of the time the ship was loading/unloading. About 10% of the time the vessel was sailing in narrow waters; predominantly through the Kiel Canal. The rest was spent waiting. For the purposes of the assessments covered in this deliverable, only the open sea navigation phases were considered.

The Enkye is equipped with a Wartsila model 9L20 engine, capable of developing a maximum power of approximately 1700 kW. According to the recorded data, it appears that during navigation the main engine is used for approximately 30% of the available power. In particular, it was measured an average power delivered during navigation equal to 591 kW ($P_{engine} = 591 \text{ kW}$), which was used as reference parameter to perform the calculations concerning the available waste heat.

Using the technical data relating to the engine cooling circuit, it is possible to calculate the thermal power that is dissipated by the engine during navigation, using the following equation.

$$\dot{Q}_{wasted} = \dot{V} * Cp * \Delta T \quad [\text{Eq. 9}]$$

Where:

- \dot{V} is the main engine cooling circuit volumetric flow rate ($\dot{V} = 12.04 \frac{\text{l}}{\text{s}}$)
- Cp is the water thermal capacity ($Cp = 4.2 \frac{\text{kJ}}{\text{kg} * \text{K}}$);
- ΔT is the difference between the Tout and Tin of engine cooling circuit ($\Delta t = 3 \text{ K}$)

Therefore, the available wasted heat is equal to 151.70 kW, 25.67% of generated power, as represented in Figure 11.

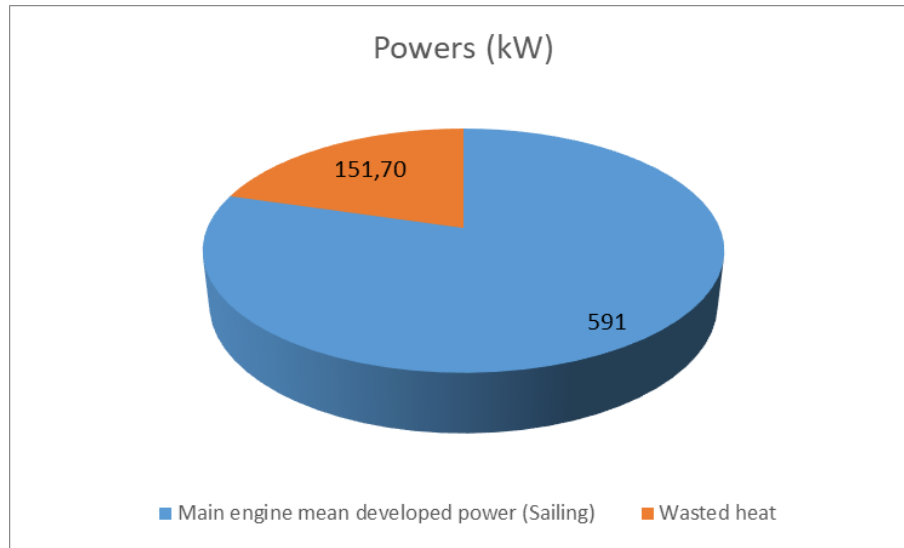


Figure 11: Developed power during sailing and available wasted heat.

4.1.2.1 Adsorption chiller

Assuming that the EER (Energy Efficiency Ratio) of the adsorption machine is equal to 0.4 ($EER_{ads} = 0.4$), the theoretically available cooling power, calculated using [$P_{cooling_th} = \dot{Q}_{wasted} * EER_{ads}$], is $\dot{Q}_{c-requested} = 60.68 kW$, as represented in Figure 12.

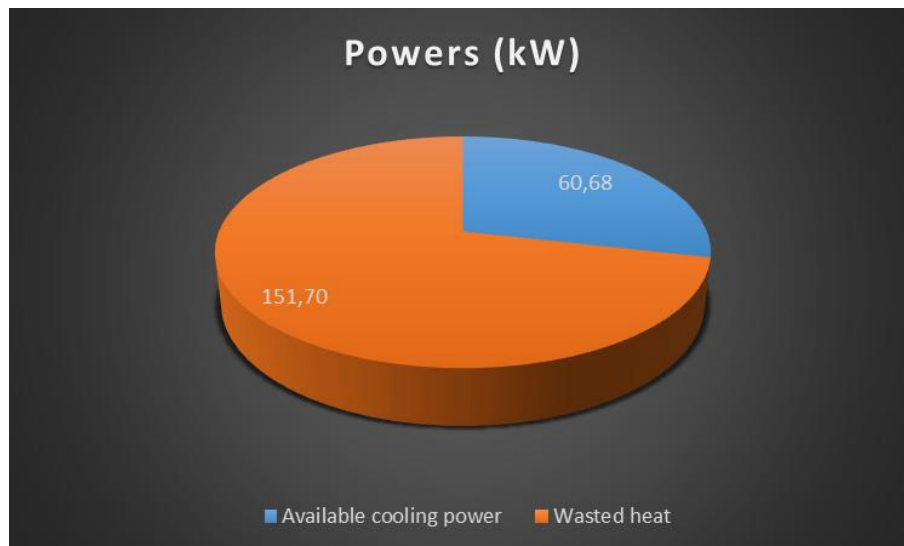


Figure 12: Available cooling power ($\dot{Q}_{c-requested}$) considering the EER of adsorption chiller.

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Since the MV Enkye is mainly used in the seas of Northern Europe, no specific cooling demand are reported, other than that necessary for some specific areas of the vessel (e.g. main control room, crew dormitory, etc.). However, this refrigeration capacity could be used if this vessel, or a similar one, would be used for navigation in warmer climates (e.g. Mediterranean sea). Likewise, the refrigeration power generated by the adsorption machine could be used for desalination of sea water, both for the crew and for other on-board uses.

The adsorption machine main parameters have been already shown in Table 3. To develop the theoretically available cooling power, the installation of 2 modules is enough. According to the monitoring performed in 2023, the average sailing time is 43 h ($t_{sailing} = 43 \text{ h}$). The main engine efficiency has been set to $\eta_{engine} = 0.45$, therefore considering an average calorific power for HFO (Heavy Fuel Oil) of $CP_{HFO} = 42.7 \text{ MJ/kg}$, the energy and fuel consumption for the main engine and the engine for auxiliaries can be hestimated using again the equations [Eq.2] and [Eq.3] already presented in the previous section.

Table 8 shows the main results concerning the MV Enkye energy and fuel consumption.

Table 8: main results concerning consumption of main engine and engine used for auxiliaries.

Main parameters concerning fuel consumption	Value
Energy consumption (main engine)	56,473.3 kWh
Fuel consumption (main engine)	4,761.22 kg
Energy consumption (auxiliaries engine)	4,353.75 kWh
Fuel consumption (auxiliaries engine)	367.06 kg

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Also in this case to calculate the energy consumption related to air conditioning, it was considered a reference vapour compression machine with an EER equal to 2.5, which means that to generate the cooling power produced by the adsorption chiller, the power absorbed by the auxiliary generator is equal to 24.27 kW according to the [Eq.4].

Taking into account what is written in the previous paragraph, if the necessary cooling power is generated by the adsorption machine, it follows that the power developed by the auxiliary engine decreases proportionally to a value equal to 16.23 kW. As already done for the Elyros, it is possible to calculate the energy consumption of the auxiliary engine when the adsorption chiller is installed on board, calculated according to the following equation, considering the efficiency of engine for auxiliaries equal to 0.4 ($\eta_{aux\ engine} = 0.4$) which, using [Eq.5] is equal to 219.99 kg.



Figure 13: Energy and fuel consumption of auxiliary engine.

The installation of adsorption chiller, for cooling or desalination, is able to save more than 140 kg of HFO, which is nearly 60% of fuel saving, if referred to the auxiliaries boilers, as represented in Figure 13.

4.1.2.2 ORC and Isobaric Engine

Similarly to what already shown for the Elyros, also for the MV Enkye it was assumed that the waste heat to operate the ORC is taken from the exhaust gases. Assuming that approximately 30% of the available power is dissipated through the exhaust gases and assuming that only 30% of the heat contained can be recovered, a theoretical power of over 53.19 kW is available during sailing. It follows that, using [Eq.6] the ORC system could develop 4.26 kW of electrical power.

The fuel consumption of the engine used for the auxiliaries can be therefore further reduced to 113.60 kg, which means that is possible to reduce the HFO consumption by 69%.

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Unlike what was already seen for the Elyros, in the case of the Enkye, also given the smaller size of the ship, it was decided to evaluate the impact on consumption due to the installation of the ORC system, alone, and of this in addition to the Isobaric Engine. In this case, the simultaneous presence of the adsorption chiller was not considered. The Isobaric Engine draws power from waste heat available from the main engine cooling circuit, while the ORC is powered by heat from the exhaust gases. Table 9 shows the results of this evaluation.

Table 9: Results concerning fuel saving using ORC, Isobaric Engine, or both.

Estimated fuel consumption (AUXILIARY ENGINE with ORC)	346.34 kg
Estimated fuel saved (ORC only)	20.72 kg
Percentage of saved fuel on fuel consumption (ORC only)	5.6%
Estimated fuel consumption (AUXILIARY ENGINE with Isobaric Engine)	352.60 kg
Estimated fuel saved (Isobaric Engine only)	14.46 kg
Percentage of saved fuel on fuel consumption (Isobaric Engine only)	4.2%
Estimated fuel consumption (AUXILIARY ENGINE with ORC+Isobaric Engine)	331.09 kg
Estimated fuel saved (Isobaric Engine only)	35.97 kg
Percentage of saved fuel on fuel consumption (Isobaric Engine only)	9.8 %

4.1.2.3 eSails

To evaluate the effect of installing the eSails on board the Enkye, the calculations already reported in the case of the Elyros were repeated. In this case, however, both the type of sails considered (22x4.5 and 18x4.5, see Table 1) and their number (2 instead of 3) were changed. **Error! Reference source not found.**The calculation was performed using [Eq. 7] and [Eq.8], and the achieved results are summarized in Table 10 as well as in Figure 14.

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Table 10: Fuel saving combining the different technologies (eSail 22x4.5).

	Saved fuel (kg)	% on Fuel consumption of Main engine + Auxiliaries engine
eSail + Adsorption chiller	1,398.07	27.26
eSail + Adsorption chiller + ORC	1,431.54	27.91
eSail + ORC	1,198.80	23.38
eSail + ORC + Isobaric Engine	1,214.05	23.67

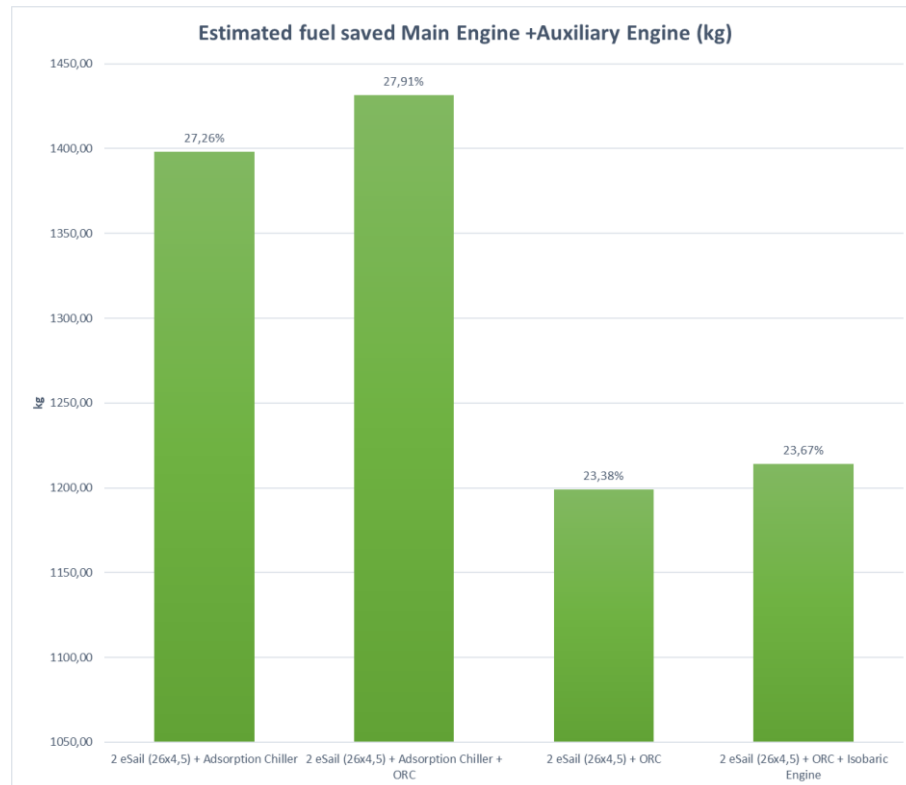


Figure 14: Evaluation of possible fuel saving by the integration of different technologies.

Table 11 and Figure 15 show the results of the same calculations considering the eSail 18x4.5, instead of 22x4.5.

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technologies for onboard integration**

Table 11: Fuel saving combining the different technologies (eSail 18x4.5).

	Saved fuel (kg)	% on Fuel consumption of Main engine + Auxiliaries engine
eSail + Adsorption chiller	1,074.10	20.94
eSail + Adsorption chiller + ORC	1,107.57	21.60
eSail + ORC	874.83	17.06
eSail + ORC + Isobaric Engine	890.08	17.36

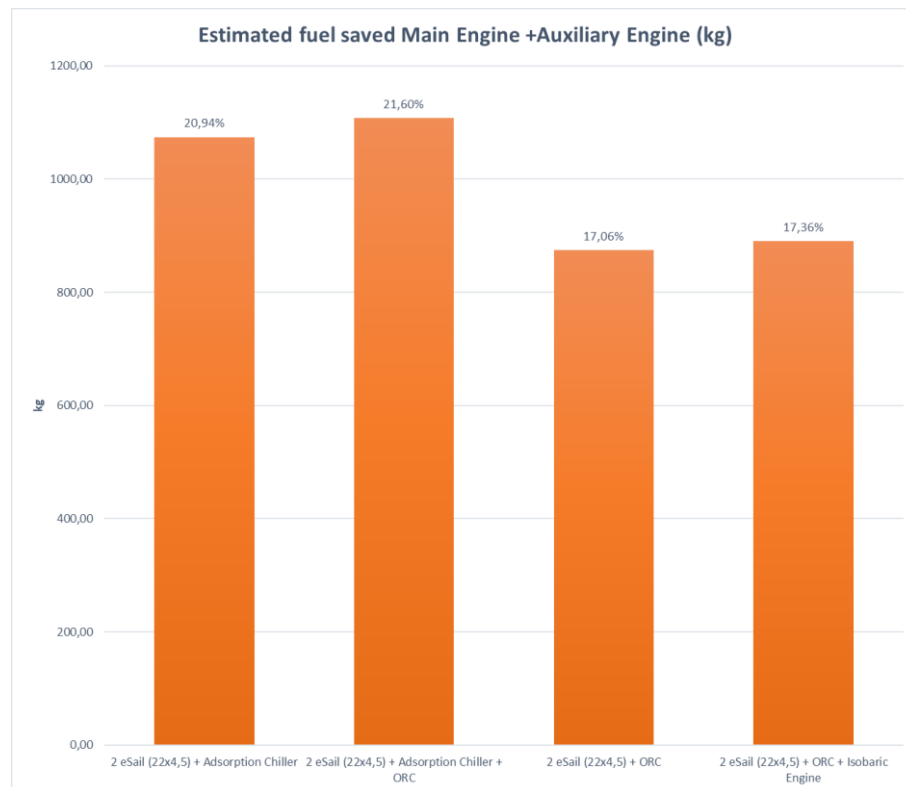


Figure 15: Evaluation of possible fuel saving by the integration of different technologies.

In evaluating the results shown above, it must be kept in mind that we considered the use of the eSails during the entire navigation period (43 h). In any case, the results obtained are very encouraging. Even if it were possible to use the eSails only for half of the sailing time (e.g. 20 h), while for the remaining

part (43 h) the wind conditions did not allow their activation, the savings that could be obtained would still be interesting, and included between 7% and 11%.

4.1.3 Large fishing vessel

The same calculations already presented in the previous sections were also performed on the fishing vessel Giacomo Giacalone I. In this case, the engine used for propulsion has a maximum power of 450 kW. As in the previous cases, it was assumed that during navigation, it is used at 30% of the useful power, therefore 150 kW.

4.1.3.1 Adsorption desalination

The fishing vessel has installed a reverse osmosis desalination plant that absorbs about 2 kW. In light of this, it was decided to simulate the use of the adsorption machine, not to generate cooling power, but to produce fresh water in place of the reverse osmosis plant. The available thermal power is always equal to 30% of the generated power, therefore 45 kW, from which it follows that, assuming an EER of 0.6 (see Table 1), the adsorption machine will be able to generate 27 kW of cooling power, corresponding to around 43 l/h of fresh water produced, which is the 54% of the actual fresh water production (80 l/h) using the reverse osmosis system.

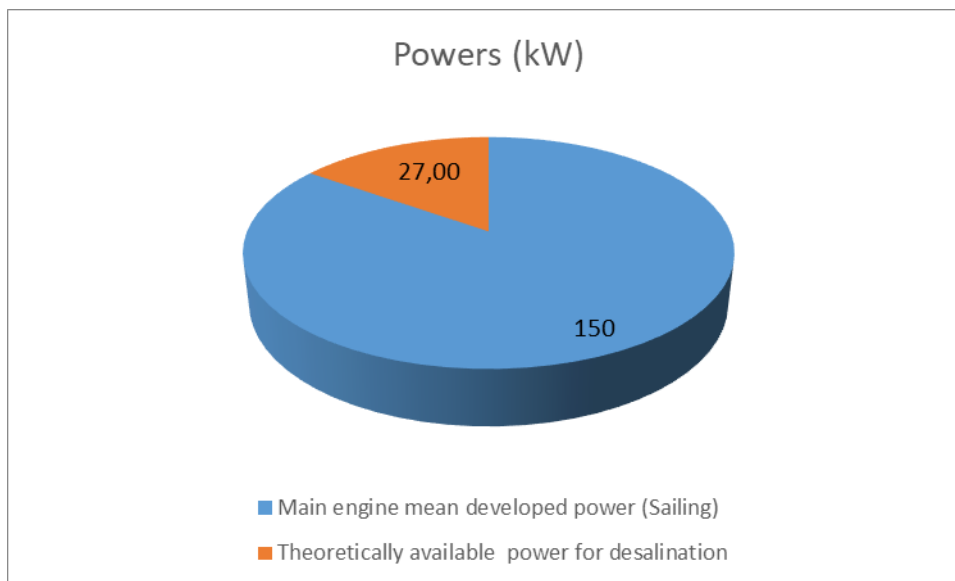


Figure 16: Comparison between the mean developed power and that available for desalination.

The auxiliary engine, used to operate the generator, delivers an average of 130 kW during navigation, to satisfy the various users (e.g. compressed air, hydraulic circuit drives, etc.). Assuming, therefore, to use the adsorption machine to generate fresh water instead of the reverse osmosis machine, the 2 kW

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absorbed by it could be partially (~54%) saved. Over the duration of the navigation (12h), this translates into an energy saving of 2.73 kg of diesel, or 0.83% compared to the total consumed by the auxiliary engine (328.81 kg). For this vessel too, it is conceivable that the heat contained in the exhaust gases could be used to power the ORC, which in this case would be able to develop just over 1 kW of electrical power, given the lower power of the main engine compared to the Elyros and the Enkye. Adding the contributions of the adsorption machine and the ORC, the total fuel saving achievable is just over 5 kg, with a saving of 1.66% compared to the reference case. In the case of Giacomo Giacalone I, due to the available space, it is not considered possible to simultaneously install the adsorption machine, the ORC and the Isobaric Engine. Consequently, the contribution of the latter has been considered as if it was installed alone. The fuel saving in this case is just over 3.4 kg, or 1.04 % of the consumption calculated in the absence of this device.

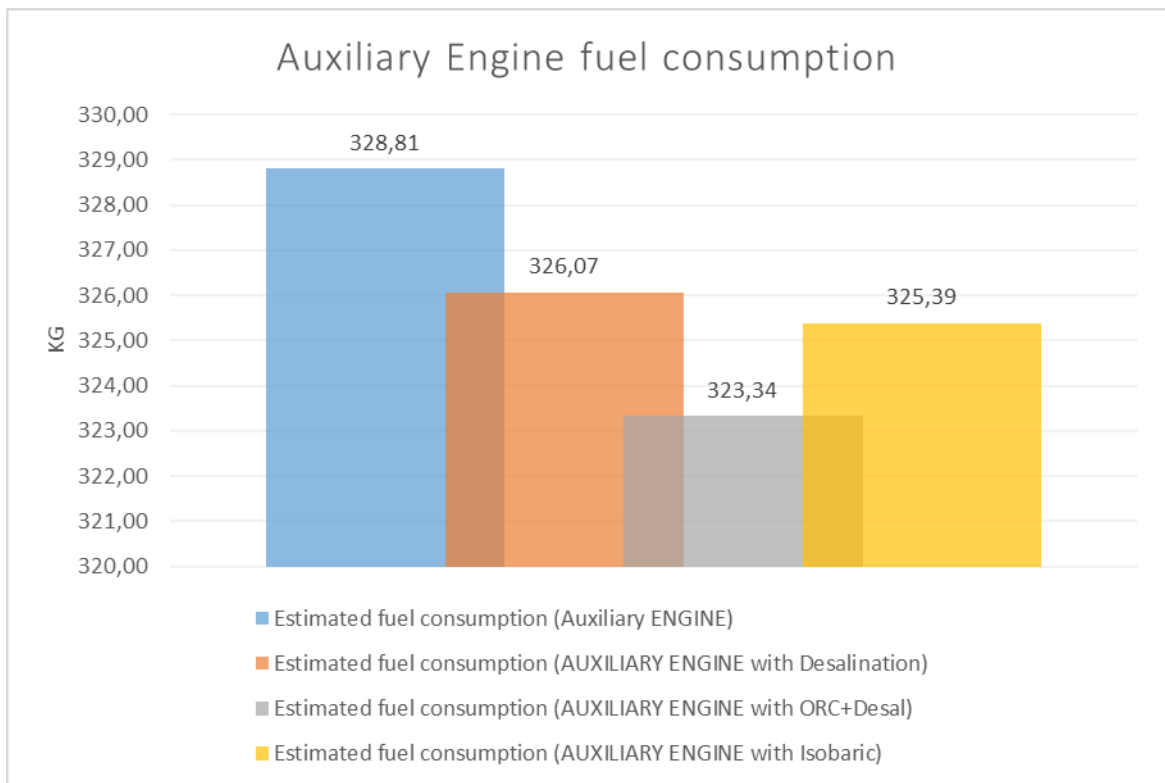


Figure 17: Comparison between the fuel consumptions integrating the different technologies.

The dimensions of the Giacomo Giacalone I do not allow the installation of an eSail, which could also compromise the stability of the vessel in adverse sea conditions, consequently, this scenario has not been analysed.

If the available space on board allowed, or if the adsorption machine were optimized to increase the specific power, it would be possible to fully satisfy the demand for desalinated water production using only waste heat. In this case, the percentage savings achievable could reach 1.5% (about 5 kg) in the case of the adsorption chiller alone, while if this were installed in conjunction with the ORC, it could reach over 2.3% (about 7.7 kg) of fuel savings.

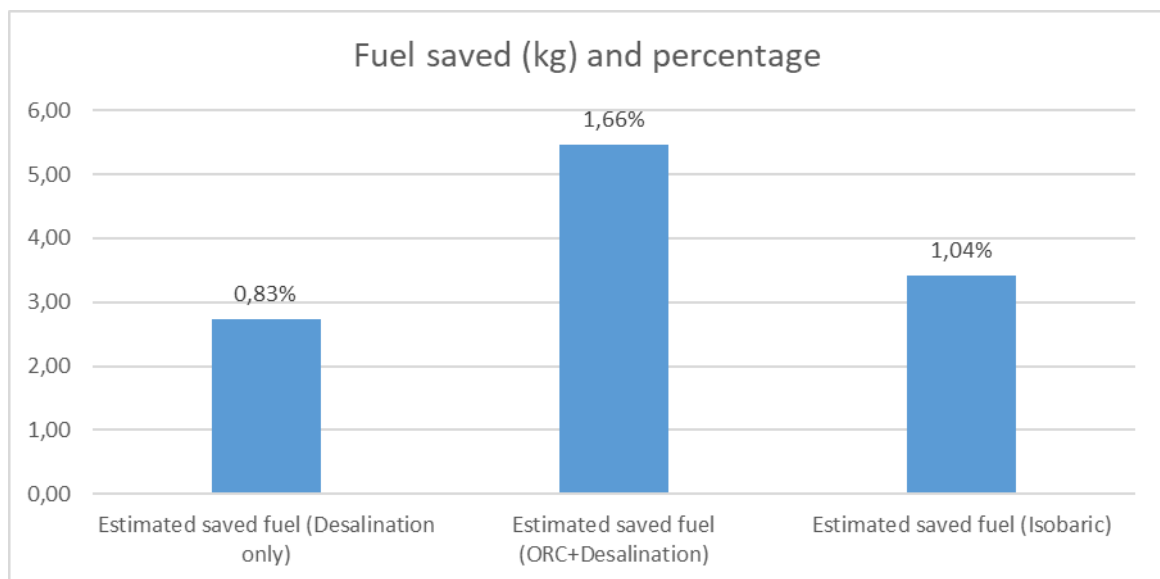


Figure 18: Possible fuel saving.

5 Guidelines for technologies upscaling

In the following paragraphs, a critical analysis of the conditions on board of each vessel according to the solutions provided above is presented. These will be used to define the proper targets to be achieved by the technologies in their upscaled version.

5.1.1 Ferry ship

Vessels of the size of the Elyros allow the integration of all the technologies developed within this project. As highlighted in the previous section, the installation of the adsorption chiller alone would allow a saving of fuel consumed by the engine that drives the auxiliaries of over 12%. Combining this technology with the ORC and the Isobaric Engine it would be possible to exceed 15%, which corresponds to over 600 kg of HFO saved during an 8-hour navigation. The size of the ship would allow for the

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installation of 3 eSails although, in the analysis presented in the previous section, the possible savings were also calculated by planning the installation of 2 eSails. This is to take into account possible limitations of available space related to the particular needs of the ship (e.g. presence of cranes, need to leave space for other equipment, etc.). In any case, the integration of the eSails with the other technologies studied in this project would allow for a saving varying between 5.63% and 7.10%, depending on the type of sail and the combination of the various technologies. In absolute terms, this translates into a fuel saving of between 950 kg and 1200 kg, over the 8 hours of navigation considered.

As mentioned at the beginning, this type of vessel does not present particular limits to the integration of different technologies, especially if they are considered from the beginning of the design. Retrofitting installation could be more problematic, especially if the technologies do not meet some specific power density targets. It is therefore essential to try to reduce as much as possible the space occupied by the different devices. In general, considering that some of these are susceptible to further improvements during the industrialization phase, it is important to evaluate solutions that allow, as much as possible, an increase in efficiency.

5.1.2 Cargo ship

In the case of the Enkye motor vessel, the technological solutions tested in the ZHENIT project find greater possibilities for integration. From the suggestions made by the designers it turned out that the problem of space on board does not appear to be a problem, if the presence of systems such as the ORC or the adsorption chiller are considered from the beginning of the construction of the vessel. Obviously, for the purposes of an ex-post installation, any optimization of the spaces, as already seen for the Giacomo Giacalone I, is fundamental. The numerical results illustrated in the previous paragraph are strongly influenced by the fact that this vessel currently sails only in the northern seas, and that the air conditioning needs are essentially related to the crew cabins. In any case, in this type of vessel, the installation of an adsorption chiller would allow, by exploiting the waste heat produced by the main engines, to generate over 150 kW of refrigeration power, which could be used both for the air conditioning of the cabins and for the production of fresh water, without requiring additional power from the engine used to operate the auxiliaries. Even if we assume (**Error! Reference source not found.**) that the power generated by the engine for the auxiliaries increases from 40 to 65 kW, to take into account the power possibly absorbed by a compression chiller with EER 2.5, the fuel saving obtainable thanks to the installation of the adsorption chiller would still be greater than 35%. Assuming to couple the adsorption chiller with the ORC, a saving of more than 60% could be obtained because in this case

two different heat sources are used (cooling circuit and exhaust gas of the main engine) to reduce the consumption of the engine for the auxiliaries alone.

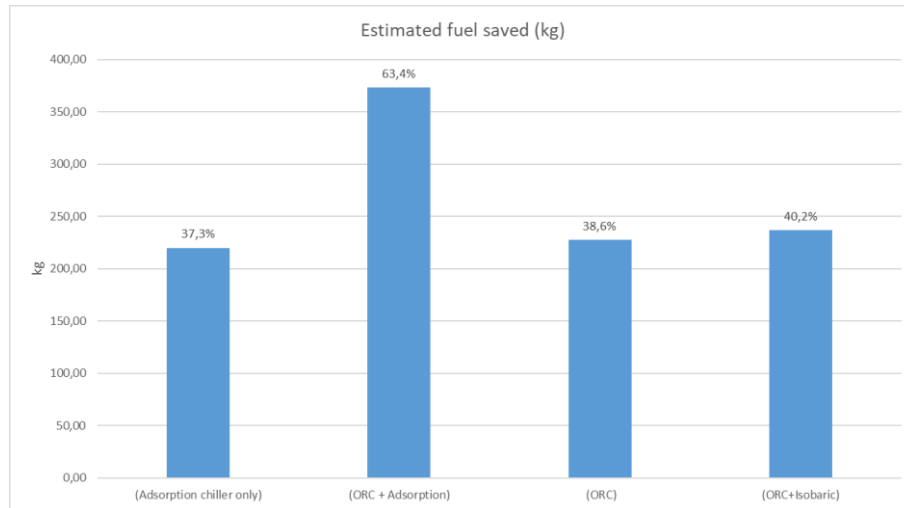


Figure 19: Potential fuel saving also considering an increase in auxiliaries engine developed power.

Unlike what was seen through the integration between adsorption chiller and ORC, the integration of ORC and Isobaric Engine does not bring the same considerable savings, due to the reduced efficiency of the latter. It therefore becomes a priority to work on these parameters, to allow boats like the Enkye, not strictly burdened by the presence of a refrigeration load, to be able to reduce fuel consumption. The values obtained, however, are satisfactory: a fuel saving of close to 9% is obtained by coupling the ORC to the Isobaric Engine. In a vessel like the Enkye, the eSails are fully integrable and show clear advantages in terms of overall reduction in consumption. In the previous paragraph it was illustrated how, depending on the different integrations and the size of the sails, the reduction in fuel consumption can easily exceed 20%. A key aspect for the upscaling of these technologies can also be given by a reduction in the space occupied by the eSails. $45m^2$ constitute a significant area, which may not be compatible with the needs of vessels of this size. A 10% reduction in the space occupied, with the same performance, would be an optimal result.

5.1.3 Large fishing vessel

The first considerations can be made on a vessel of the size and mission of the Giacomo Giacalone I. This vessel has much smaller dimensions than the others considered. The engine room does not have significant free spaces in which to install solutions that are not designed from the outset to be integrated into vessels of this size. The space occupied by the devices installed on board represents the key factor.

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Numerical results show that the integration of an adsorption machine for the production of fresh water results in fuel savings of less than 1%, with a power/volume ratio of approximately $15kW/m^3$. The low energy savings are related to the low availability of waste heat, compared to the demands of the users installed on board (production of fresh water). In this context, the key parameter to be optimized is therefore the ratio between the fresh water produced and the volume occupied by the adsorption machine. It is necessary to optimize the layout of the adsorption chiller to make it more compact and compatible with small-sized vessels such as the Giacomo Giacalone I. An increase in the power/volume ratio of at least 15% is appropriate to improve the compatibility with the small size of a vessel of this type. Furthermore, it would be appropriate to optimize the work cycle (e.g. using a more performing adsorbent material than silica gel), to increase the current Energy Efficiency Ratio (EER) from 0.6 up to 0.75. This increase, starting from the results presented in the previous section, would lead to the possibility of increasing the water production, with the same waste heat, from 43 l/h to almost 54 l/h.

Greater energy savings have been achieved through the integration of ORC and Isobaric Engine. This is because these two technologies, as already illustrated in the previous section, do not conflict with each other, since they use different thermal power sources: the engine cooling circuit for the Isobaric Engine, the exhaust gases for the ORC. The combination of these technologies has shown the possibility of achieving fuel savings of over 1.6%. In this case, the weak point lies in the low efficiency guaranteed by these technologies (about 8% for the ORC and 5% for the Isobaric Engine). Nonetheless, their combination has proven to be particularly effective for a vessel such as the Giacomo Giacalone I. The use of just one of these technologies is less attractive. Moreover, in both cases, a specific target in terms of power density needs to be guaranteed, to be easily integrated inside the engine room with limited space availability. A minimum target of $20 kW/m^3$ should be considered.

Finally, the use of eSails, at least in the type tested in ZHENIT, does not appear to be applicable for vessels with the dimensions of the Giacomo Giacalone I, since they are not compatible with the space available on board and can cause serious stability problems for the vessel.

5.1.4 Targets to be met by ZHENIT technologies for future upscaling and marketability

While it is true that waste heat (or wind in the case of eSails) is used to power these systems, it is also true that the diffusion of these technologies is strongly linked to their technical acceptability. Therefore, they must be easily integrated avoiding excessive issues in their practical application.

Table 12 summarizes the key parameters, the optimization of which could allow a faster industrial scale up of the different technologies.

Table 12: Key parameters for technologies upscale.

Technology	Key parameter	Range of expected improvement
Adsorption Chiller	Power/volume ratio	+15%-20% (up to 20 kW/m ³)
	EER in cooling mode	0.5 – 0.6
	EER in desalination mode	Up to 0.75
ORC	Efficiency improvement	10% - 20% (up to 10 %)
	Expected power density	20 kW/m ³
Isobaric Engine	Efficiency improvement	10% - 20% (up to 6 %)
	Expected power density	20 kW/m ³
eSail	Occupied area reduction	8% - 10% (down to 40 m ²)

6 Conclusions

This deliverable focuses on the definition of future targets to be met by the ZHENIT technologies in view of their upscaling and their possible commercialization. This is achieved by performing a detailed analysis of the possible integration of the technologies on board of three reference vessels, identified by the consortium as replication cases, namely, a large ferry, a cargo vessel and a large fishing vessel. These three examples were selected to cover a large portion of possible applications in terms of size as well as mission profile of the vessels.

The ferry vessel represents the most flexible one in view of future integration on board, indeed it has a larger space availability and several different on board demands (i.e. electricity, heating, cooling) which fit with all the ZHENIT technologies. It has to be pointed out that this ferry can be somehow considered close to a cruise ship, thus being even more representative of the existing real cases. The current ZHENIT technologies show the ability of covering a large portion of energy demand on board. Specifically, the overall fuel saving of an integration comprising adsorption chiller, ORC, Isobaric Engine and eSail amounts up to 1200 kg for a sailing route of 8 h.

The cargo vessel also represents an interesting case, since the space availability should guarantee quite a flexibility in integrating the technologies on board. In this case, given the specific application of the vessel, the cooling demand is highly dependent on the sailing area. Indeed, the one specifically identified is mostly sailing in Northern Europe, thus representing a perfect case were ORC and isobaric engine, along with eSails are integrated on board. In this configuration, up to 1200 kg of fuel can be saved for a reference route characterized by 43 hours of sailing. In case of a similar vessel employed in warmer areas, e.g. Mediterranean sea, the complete integration with the adsorption chiller would increase the fuel saving up to 1400 kg, under the same sailing profile.

The fishing vessel, even if representing a specific case of large vessel for catching periods up to 30 days, is characterized by very limited space on board for installation of new technologies. Accordingly, in this case the power density of the different technologies becomes even more critical. Generally speaking, the integration of adsorption desalination unit or electric generation provided by ORC and Isobaric Engine seem the most appropriate ones. The former (alone) can guarantee alone around 2.7 kg of savings while the integration between adsorption desalination unit and ORC achieves up to 5.4 kg of fuel savings. The Isobaric Engine (alone) is able to achieve until 3.4 of fuel saving. Differently, eSails are not suitable for this kind of vessels. Unfortunately, among all the possible cases, this one is the less relevant

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for future ZHENIT integration given the limited waste heat availability and space for integration of all the proposed technologies.

Starting from these preliminary calculations, some preliminary guidelines for making the technologies more attractive in future integration on board were defined. Generally speaking, an increase in energy efficiency conversion up to 20% for all the proposed technologies is desirable. This can be met by improving the components' design as well as identifying novel and more efficient working fluids for the different conversion cycles. For what it concerns the space requirement, this has a main impact on small vessels such as the fishing ones. In these cases, at least 20 kW/m³ for all the proposed technologies represents a relevant target. It can be met by a proper design of the technologies at higher TRL. Of course, a more compact technology can be also useful in larger vessels to save space and allow the installation of higher capacity on board. Regarding the eSails, in order to allocate a larger number of sails on the deck, a reduction of the footprint is suggested, which needs to be verified from the sail stability point of view.

7 Annex I

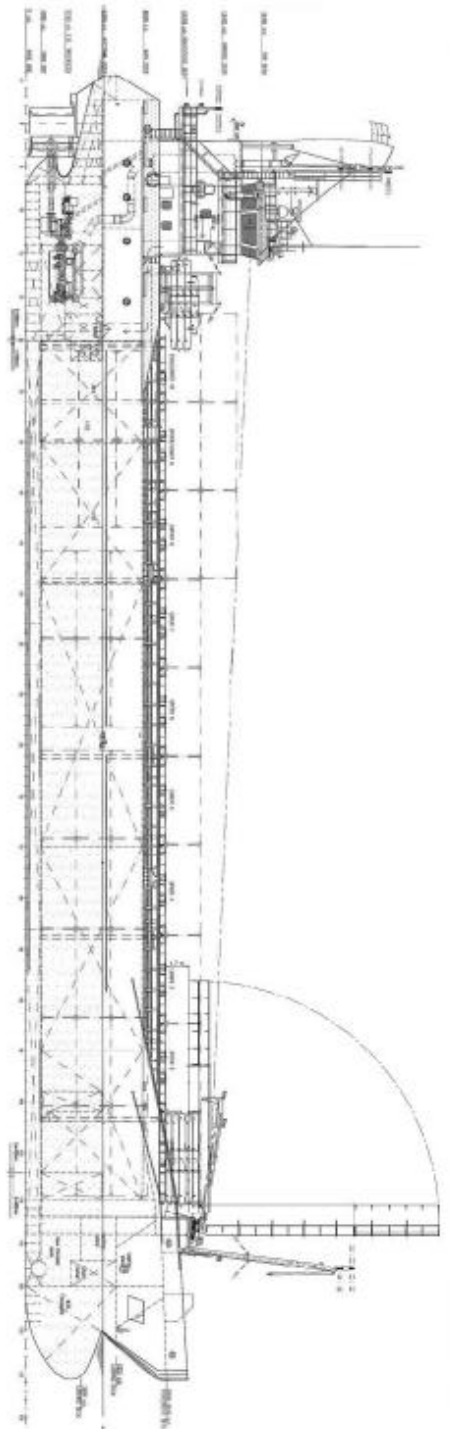


Figure 20: Schematic view of MV "Enkye"

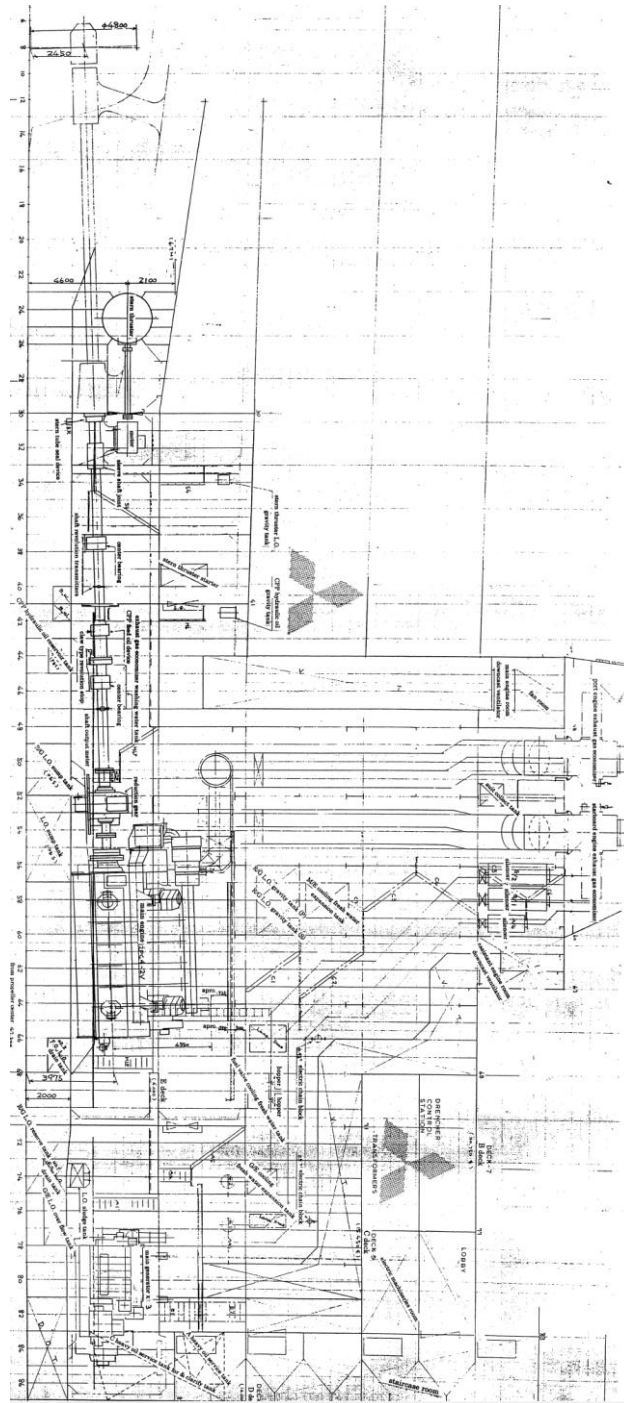


Figure 21: Section of the thruster of the Elyros vessel.



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