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Innovative waste heat valorisation technologies for zero-carbon ships – A review

Robin Fisher [a], Lorenzo Ciappi [a], Pouriya Niknam [a], Konstantinos Braimakis [b], Sotirios Karellas [b], Andrea Frazzica [c], Adriano Sciacovelli [a,*]

[a] *School of Chemical Engineering, University of Birmingham, Birmingham, UK*
[b] *School of Mechanical Engineering, National Technical University of Athens, Athens, Greece*
[c] *Istituto di Tecnologie Avanzate per l'Energia "Nicola Giordano", Consiglio Nazionale delle Ricerche (CNR), Messina, Italy*

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ABSTRACT

The growing intensity of international commerce and the high share of total global greenhouse gas emissions by the maritime sector have motivated the implementation of regulations by the International Maritime Organisation to curtail vessel emissions. In this context, waste heat recovery (WHR) is an effective way to improve ship energy efficiency, lower amounts of wasted energy rejection to the environment, and therefore ultimately curb green-house gas emissions. Presently, there exists a heterogeneity within the body of literature concerning WHR technologies for on-board applications, study scope and results, complicating the interpretation and cross comparison of the outcomes. Sporadic attempts have been made to review and systematise this landscape, leaving some key areas uncovered. Therefore, the present article aims at filling these gaps by providing and holistic review of WHR technologies development and on-board applications. Further, the energy systems and available waste heat characteristics in large vessel types are overviewed, before both existing and developmental on-board waste heat recovery technologies for maritime applications are reviewed. Emphasis is placed on the performance of these technologies within the broader on-board energy system. Common key performance indicators are drawn from existing systems, experimental prototypes, and simulations, to quantitatively compare the different technologies. This review indicates that a wide range of technological options for embedding waste heat recovery in on-board energy systems are emerging. In particular, traditional turbocompounding is already fully implemented within the marine waste heat recovery (WHR) context. Conversely, ORC systems and absorption refrigeration systems have not yet been suitably adapted for marine applications due to a lack of research and prototypes, despite their deployment in conventional WHR contexts. Other technologies, such as thermal energy storage devices, hybrid refrigeration systems, isobaric expansion engines, Kalina Cycles, and adsorption desalination and cooling systems, are still at the research and development stage, while thermoelectric generation systems continue to incur high deployment costs. The development of research on these innovative technologies, the reduction of their cost and their synergistic integration could lead to significant improvements inengine fuel efficiency and emissions reduction, especially when coupled with existing waste heat recovery measures.

1. Introduction

Approximately 3 % of total greenhouse gas (GHG) emissions can be attributed to the global fleet of vessels weighing above 100 tons [1]. As noticeable in Fig. 1, it is envisioned that international trade will continue to expand in the near future [2]. Thus, in line with the United Nations Sustainable Goal 13 named "Climate Action" [3], the International Maritime Organisation (IMO) aims to curtail by 50 % GHG emissions of ships by the year 2050 [4]. Various strategies exist to approach reducing GHG emissions from ships, as discussed in a number of research articles reviewing the possible strategies for shipping decarbonisation [1,5,6,7]. Reporting done by the IMO [8] describes 50 energy-efficiency improvement measures, with an in-depth analysis of 22 of these measures. These include: utilisation of alternative, cleaner fuels (LNG, hydrogen, ammonia and advanced bio-fuels), the integration of renewables on-board (solar PV for example), alternative means of propulsion, improvement of the current propulsion technology (large

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* Corresponding author.
E-mail address: a.sciacovelli@bham.ac.uk (A. Sciacovelli).

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Nomenclature

Abbreviations

ABC	Absorption Cycle
CHP	Combined Heat and Power
COP	Coefficient Of Performance
DWT	Dead Weight Tonnage
GHG	Green House Gas
HRSG	Heat Recovery Steam Generator
HT	High Temperature
IEE	Isobaric Expansion Engine
IMO	International Maritime Organisation
KPI	Key Performance Indicator
LT	Low Temperature
LTES	Latent Thermal Energy Storage
MED	Multiple Effect Desalination
MSF	Multiple Stage Flash
O&M	Operation and Maintenance
ORC	Organic Rankine Cycle
PCM	Phase Change Material
PTG	Power Turbine Generator
PT	Power Turbine
R&D	Research and Development
SCP	Specific Cooling Power
SDWP	Specific Daily Water Production
SMCR	Specified Maximum Continuous Rating
SRC	Steam Rankine Cycle
ST	Steam Turbine
STES	Sensible Thermal Energy Storage
STG	Steam Turbine Generator
TCS	Thermochemical Energy Storage
TEG	Thermo Electric Generation
TES	Thermal Energy Storage
VCC	Vapour Compression Cycle
WHR	Waste Heat Recovery
WHR-HX	Waste Heat Recovery Heat Exchanger
WHRS	Waste Heat Recovery System

Symbols

C	Cost [€/kW]
C_p	Specific Heat [J/kg/K]
E	Energy [J]
L	Latent Heat [J/kg]
m	Mass [kg]
$\dot{m}$	Mass Flow Rate [kg/s]
N	Number of cycles [-]
P	Power [kW]
P_{cool}	Cooling power [kW]
P_{mec}	Mechanical power [W]
P_v	Volumetric power [W/m^3]
Q	Power / Energy Rate [kW]
T	Temperature [K]
t	Time [s]
W	Work [kW]
η	Efficiency [-]
ρ	Volumetric Density [kg/m^3]

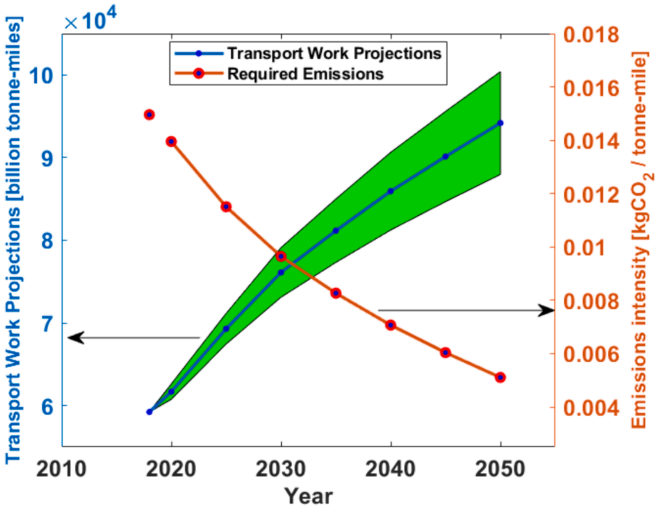

Fig. 1. (left) Shipping transport work projections by the IMO [9], averaged from 12 gravity model scenarios with equal likelihood assumed, green area represents the standard deviation. (right) Required emissions intensity reduction between present day and 2050 to match UN targets, linear correlation assumed between 2012 and the 50% CO_2 emissions reduction by 2050, normalised by the projected transport-work from IMO for each year. Tonne-miles signifies the transport of one ton of freight over a nautical mile.

two-stroke diesel engines) to increase their efficiency directly at the combustion stage or indirectly through effective exhaust recirculation and reutilisation (turbocharging), the deliberate reduction of speed to optimise the operation of the engine (slow steaming), or improving hull coatings and hull shape.

While only briefly discussed as an operational strategy in the previously mentioned reviews, waste heat recovery (WHR) can abate shipping-related GHG emissions [7] by improving the overall fuel energy utilization and thus overall ship energy efficiency. Indeed, typically only 50 % of fuel is actually converted to mechanical energy in large two-stroke diesel engines [10], the primary propulsion technology in the vast majority of ships above 100 tons [11]. The remaining 50 % of fuel energy is lost as waste heat through various streams, namely exhaust gases, cooling fluids and thermal radiation. Similar values of engine thermal efficiency are expected also in future ship engines employing instance of green fuels as methanol, which emphasizes that relevance of waste heat recovery will likely persists even in the instance maritime sector fully switches to sustainable fuels.

The viability of WHR to improve fuel efficiency and abate GHG emissions has been evidenced in various studies. For example, WHR systems with payback times around 2 to 5 years, capable of lowering fuel utilisation by 4 % to 16 % respectively, were shown as achievable by Baldi and Gabrielli [12]. Reviews by Shu et al. [13] in 2013, and by Singh and Pedersen [11] in 2016 outlined the marine WHR state-of-the-art. However, they show discrepancies in the categorisation and selection of WHR technologies; further the existing reviews either sparsely consider or ignore non-conventional, emerging WHR recovery technologies. For instance, the review by Shu et al. selectively deals with WHR based on turbine devices as Turbochargers and Rankine cycles. Other WHR methods should be discussed such as refrigeration systems, which feature in the Singh et al review. Several reviews target either a type of WHR or a specific WHR application. Palomba et al. [14] investigated WHR to thermally drive on-board cooling and refrigeration systems for fishing boats. Xu et al. [15] specifically reviewed refrigeration technologies, with some discussion surrounding components. Zhu et al. [16] focused their review on WHR through bottoming power cycles as Rankine, Kalina and CO_2-based power cycles. Additionally, the mentioned reviews limitedly discuss waste heat recovery heat exchangers, despite being a staple in terrestrial waste heat recovery technology [17,18]. A summary of existing WHR reviews and the technologies covered as well as the is shown in Table 1. Turbochargers were omitted from the present review because they should be considered as features of engine technology rather than WHR technology.

1.1. Motivations, aims and novelty of the present review

Vessels are evolving, and the modern paradigm is to consider them as multi-energy systems, which are systems in which energy demands, utilities and energy loads are designed synergistically to interact optimally with each other [19]. In the light of the multi-energy system paradigm and considering the landscape of current WHR technology literature reviews presented in the previous section, where a comprehensive, quantitative, and up-to-date review of all current realistic options for on-board WHR is missing, this article aims to provide a systematic, complete, holistic, and updated review of current WHR technology for large on-board energy devices. Previous marine WHR technological reviews either deal with a smaller subset of WHR technologies, or focus primarily on heat-to-heat, heat-to-power, or heat-to-cooling technologies.

Furthermore, outside the need for a comprehensive review encompassing current marine WHR technological solutions, there are also innovative, novel technologies that existing WHR reviews currently overlook in the context of marine applications. Some innovative enabling solutions, particularly adsorption desalination, on-board thermal energy storage and other emerging WHR technologies have a growing body of results and reviews for terrestrial applications but not for onboard applications. Given the existence of these emerging technologies and the lack of reviews analysing their impact in on-board energy systems, there is now the need for the systematic analysis and synthesis of works on the topic of these technologies in view of homogenising their techno-economic data and enabling their cross comparison.

Thus, the present work aims to address the identified gaps in the marine WHR literature to provide a new systematic thinking and framework around WHR solutions in highly efficient on-board energy systems, to reach the overarching objective of decarbonising the maritime sector and more broadly industry. The present review therefore aims to cover the following research needs: an all-encompassing review of marine WHR technologies that deal with heat-to-heat, heat-to-power, heat-to-cooling and heat-to-fresh water; a modern literature review covering modern, novel WHR technologies which have found applications in terrestrial applications but have yet to be reviewed for on-board energy devices despite their potential; the need for a marine literature review with a systematic evaluation framework of WHR technology performance through a set of key performance indicators (KPIs).

Table 1
Summary of marine WHR technological reviews in the literature, and the technologies discussed in each review and the present review.

	Shu et al. [13]	Singh et al. [11]	Xu et al. [15]	Zhu et al. [16]	This review
Waste Heat Recovery Heat Exchangers					x
Turbochargers	x	x			
Hybrid turbocharger		x			
Turbo-compound system		x			x
Absorption Refrigeration	x		x		x
Adsorption Desalination and Refrigeration	x		x		x
Hybrid Refrigeration			x		x
Thermoelectric Generation	x	x			x
Organic Rankine Cycle	x	x		x	x
Kalina Cycle		x		x	x
Thermal Energy Storage					x
Isobaric Expansion Engines					x

Thus, by addressing such areas of WHR in on-board energy systems, the present work uniquely informs potential stakeholders of application aspects of on-board WHR, with the following contributions:

- Aggregation and discussion of cross-comparable key performance indicators of a complete set of WHR technologies in a clear manner which was not previously available.
- Review of several innovative WHR technologies such as thermal energy storage and isobaric expansion technology, which have gathered interest in terrestrial energy applications but require discussion for on-board applications. For both the novel and the better-known technologies such as ORC, performance data with a focus on marine performance has been aggregated in a way that was not previously available.
- Discussion of potential practical integration of WHR technologies in a typical energy system on ships, with the characterisation of available waste heat, to provide a previously unavailable system archetype for an equivalent cross-comparison of technology performance.

2. Archetype of an on-board energy system

The International Maritime Organisation (IMO) lists 19 vessel types under which most ships in the global fleet can be categorised [9]. To each vessel type can be ascribed a specific size category, average main and auxiliary engine power, dead weight tonnage (DWT), typical voyage duration, length and average speed, fuel consumption, emissions, among other characteristics. IMO vessel types are broadly organised into four so-called vessel type groupings: '*Cargo*' ships (13 of the 19 types), '*non-merchant*' ships (2 of the 19 vessel types, yachts, and fishing vessels), '*work vessels*' (3 vessel types) and '*non-seagoing merchant*' vessels. These vessel type groupings are summarised in Table 2 along with each grouping vessel count, fraction of the total fleet, DWT, and fraction of the global DWT. 'Cargo' type ships represent 48.8 % of the total ship count; and 94.8 % of total dead weight tonnage of the global fleet. 'Work vessels' and 'non-merchant vessels' represent 28.4 % and 22.1 % of the global ship count respectively, but respectively only 4.71 % and 0.26 % of the total DWT of the global fleet. Other types represent less than 1 % in terms either of ship count or global fleet DWT. Cargo ships therefore represent most vessels worldwide in terms of ship count and particularly as a fraction of the global fleet total DWT. Thus, the description of the archetypical energy system for cargo ships can be considered representative of on-board energy systems when analysing the integration and performance of WHR for marine applications in the scope of this article.

2.1. On-board energy system architecture

An on-board energy system consists in the machinery designed to meet the main sources of energy demand of ships as propulsion,

Table 2
Vessel type IMO subgrouping: vessel count and global dead weight tonnage [9].

Vessel Type Grouping	Vessel count [number of ships]	Fraction of vessel count [%]	Global DWT [tons]	Fraction of global DWT [%]
Cargo	58,607	48.90 %	$1.85 \bullet 10^9$	94.82 %
Work Vessels	33,986	28.46 %	$9.18 \bullet 10^7$	04.71 %
Non-Merchant	26,388	22.14 %	$5.08 \bullet 10^6$	00.26 %
Non-Seagoing	645	00.50 %	$4.00 \bullet 10^6$	00.21 %

manoeuvring, cargo handling, crew and passenger comfort, electrical, heating and cooling demand, and freshwater production. The schematic representation of an archetypal energy system on a cargo vessel is shown in Fig. 2.

On-board energy devices of large vessels powered by 2-stroke internal combustion Diesel engines essentially revolve around meeting two primary needs: the conversion of chemical energy of fuel to mechanical energy for propulsion through main engines, and the conversion of chemical energy of fuel to electrical energy for auxiliary demands through auxiliary engines. In both main and auxiliary engine types, part of the chemical energy of the fluel is also converted to waste heat which can in turn be converted to either electrical/cooling energy or directly used to satisfy the various on-board thermal requirements, via the on-board waste heat recovery system (WHRS).

Propulsion in large modern ships is conventionally delivered by a submerged propeller connected to the main engine. Other noteworthy propulsion devices are sails, wind rotors, or in some cases a type of atmospheric propeller, which are not submerged in water. Conventional propulsion systems can broadly be divided into two types depending on how the propeller is coupled to the prime mover [20]. On the one hand, mechanical propulsion systems, in which the propeller is connected to a thermally driven engine via a gearbox, with auxiliary diesel gensets to provide the electrical load. In such systems the main engine system is either a single large engine, or a set of smaller engines working in tandem. The archetypal on-board energy system shown in Fig. 2 is assumed to be mechanically propelled. On the other hand, electrical propulsion systems, where the propeller is driven by an electric motor. In such systems, in modern cases, auxiliary electric loads are delivered by the same system which guarantees high efficiency [21]. Electrical propulsion systems can commonly be found in ships with high auxiliary electrical loads, such as cruise ships like hotel loads or when the operational profile is varied.

The objective of Fig. 2 is to present an archetypal on-board energy system as a template of an energy system that is relevant regardless of the specific type or class of vessel. It is worth noticing that the percentage of energy referrable to the specific technologies tends to be peculiar of each vessel and dependent on its functioning as, for example, cruising and hotelling operations. Moreover, it is affected by high uncertainties. Nonetheless, some details regarding the typical values of energy streams are provided throughout the paper, with a particular focus on thermal energy streams.

The machinery constituting the on-board energy system also comprises the energy conversion sub-systems designed to convert the chemical energy of fuel into a convenient energy form to meet the on-board demands [22]. On-board demands can be subdivided into:

- Thermal demands, which include the heating of various elements of machinery with steam such as heavy fuel oil and lubricant tank heating, engine pre-heating, waste incineration, the production of freshwater, air conditioning with heating, hot water production and cooking. In order to satisfy the thermal demands, ships will often feature either a single or multiple pressure level steam generation system [23], thermally driven by an exhaust gas economiser (EGE) and potentially preheated by other waste heat streams as explained in the following section.
- Cooling demands: either seawater cooling system or freshwater cooling system, which are generally divided into low temperature (LT) and high temperature (HT) cooling loops, and air conditioning with cooling.
- Electrical demands: bow thruster, lighting, cargo handling and engine rooms [24].

The on-board energy system illustrated in this section feature varying levels of internal waste heat recovery, typically some type of heat exchanger with exhaust gas on the hot side to fulfil some of the on-board heating demands, or in some cases a steam or power turbine in a so-called turbo-compounding system. Ultimately, current on-board energy systems have significant untapped WHR potential, as detailed in the next section, and thus GHG emissions can be meaningfully reduced. The WHR technologies reviewed in this article are aimed at being integrated into advanced energy-efficient versions of such on-board energy systems. The following section aims to quantify the typical waste heat on

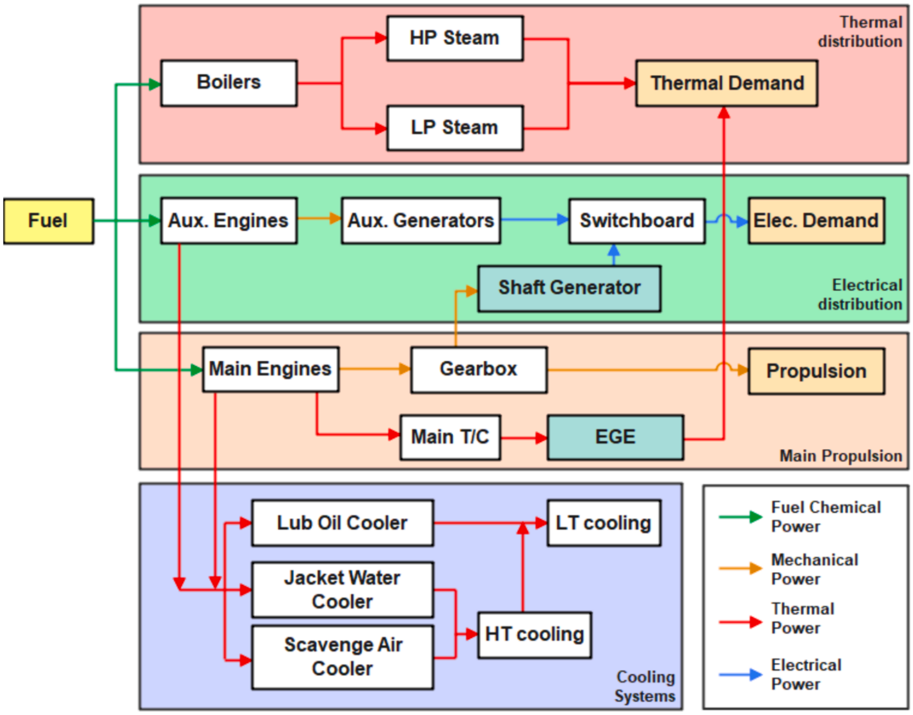

Fig. 2. Schematic representation of an archetypal on-board energy system. EGE: Exhaust Gas Economiser, HP: High Pressure, LP: Low Pressure, T/C: Turbocharger, LT: Low Temperature, HT: High Temperature.

board, which informs on the classes of WHR technology that should be considered for marine WHR.

2.2. *Main characteristics of on-board waste heat*

Waste heat characteristics were gathered and synthesised from various sources: mainly engine data such of manufacturers as MAN engine specifications [25] and Wartsila Diesel Engine project guides [26,27], scientific literature [13,28–35], theses [36–38] and the grey literature [39,40]. Data was collected surrounding temperature levels, mass flow rates and rated engine powers. The data collected allows to determine and calculate the heat rates and temperature levels of the on-board waste heat sources, as shown in Fig. 3 and Fig. 4, respectively. The rate of waste heat Q_{WH} [kW] for a given stream was calculated using **equation (1)**:

$$Q_{WH} = \dot{m}_{WH} Cp_{WH} (T_{WH} - T_{ref}) \tag{1}$$

Where $\dot{m}_{WH}$ [kg/s] is the mass flow rate of the WH stream, Cp_{WH} [kJ/kg/K] the specific heat capacity of the WH stream. Exhaust gases are the by-product of diesel fuel combustion with air; the properties and composition of exhaust gases are close to that of air with increased H_2O and CO_2 content [41]. The heat capacity can be assumed to be very close to that of hot air. Ideally it should be calculated using the exact composition of diesel engine exhaust gases which are dependent on the combustion power, engine load and composition of the air; a value of$Cp_{WH,EG} = 1.1$ kJ/kg/K is assumed in this article. T_{WH} [K] is the temperature of the WH stream, T_{ref} [K] is a reference temperature. This reference temperature is either the cold source temperature for lubricating oil and jacket cooling water assumed to be $T_{ref} = 284.15$ K, a likely average seawater temperature, such as average surface sea water in UK shelf waters over the 1880–2016 period [42], and $T_{ref} = 150^{\circ} C$ for exhaust gases, which should not be cooled below the acid dew point temperature of the Sox compounds of around 140 °C with a 10 °C safety margin as engineering practice [33,43]. These SOx compounds can react with air humidity to form sulphuric acid and damage the systems of ships. Thus, the rate of waste heat specifically in the exhaust gases reported here may be lower than other references which do not account this practical minimum temperature limit.

The rate at which waste heat is typically available onboard, compared to the power rating of the main engine at 100 % load computed using **equation (1)** and the data from the sources discussed in the previous paragraph, is shown in Fig. 3 and a near linear correlation can be observed. The evidence gathered shows that exhaust gases carry useful waste heat at a rate of ∼ 20–30 % of engine rated power, jacket cooling water at a rate of ∼ 10 % of the rated engine power, and lubricating oil at ∼ 8 %. The synthesised data presented suggests that there is significant potential of approximately 40 % of fuel energy that could be harvested as heat from the engine waste heat streams, depending on engine power and load.

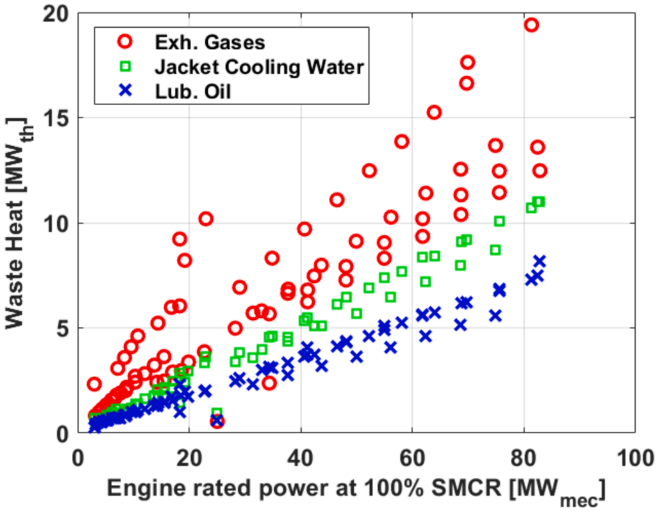

Fig. 3. Rate of waste heat in various streams as a function of main engine power.

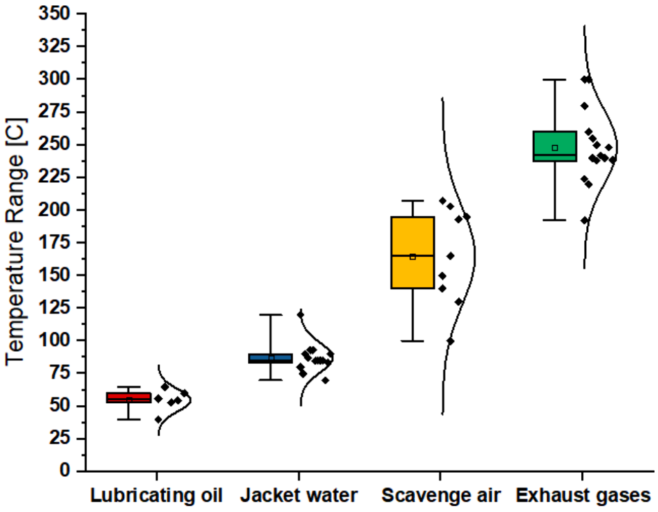

Fig. 4. Temperature levels of various waste heat streams.

While WHR solution design is dependent on the rate at which waste heat is available, waste heat temperature is also a determining factor. As will be seen in the individual WHR technology review section, various WHR-driven technologies require a minimum temperature level to function, such as evaporating a working fluid or thermally regenerating materials. Fig. 4 shows the typical temperature range of the waste heat carrying cooling streams and gases.

Modern WHR solutions have temperature requirements which are compatible with the levels found in marine WH. Data has been divided between the four WH streams. Individual dots represent the WH stream temperature data points, originating from the same sources as previously discussed, the Gaussian curves illustrate the spread of temperature data points, the boxes contain the mean (single dot inside the box) and median (line inside the box) for each WH source, while the top and bottom lines (the 'whiskers') show the minimum and maximum in the data set.

In Fig. 4, the four waste heat streams are ranked left to right in ascending order of typical temperature level: lubricating oil, jacket cooling water, scavenge air and exhaust gases. Lubricating oil circuit is the lowest temperature waste heat containing streams, between 50 °C and 75 °C. Jacket cooling water is a fluid circulating through the engine cylinder liners, cylinder covers and exhaust valves [44] which can be at temperatures around 100 °C. Scavenge air contains commonly carries a relevant amount of waste heat [20] which can be up to 200 °C in some engine configurations. Approximately half of ship waste heat is found in the exhaust gases which thus contain the highest potential for recovery.

As it was mentioned previously the total waste heat depends on the operational engine load, which is the fraction of the design power rating the engine. The proportion of time the engines operates at each load is typically reported in a so-called operational profile, an example of which is shown in Fig. 5 for a Panamax container ship [45]. As can be seen the ship spends majority of the time running the engine between 50 % and 100 %. Furthermore, operating an engine at 50 % load will result in waste heat being approximately halved compared to the full load; thus, despite the waste heat being reported previously for 100 % engine load, there is still a relevant amount of waste heat to recovery during the typical operation of a large enough ship.

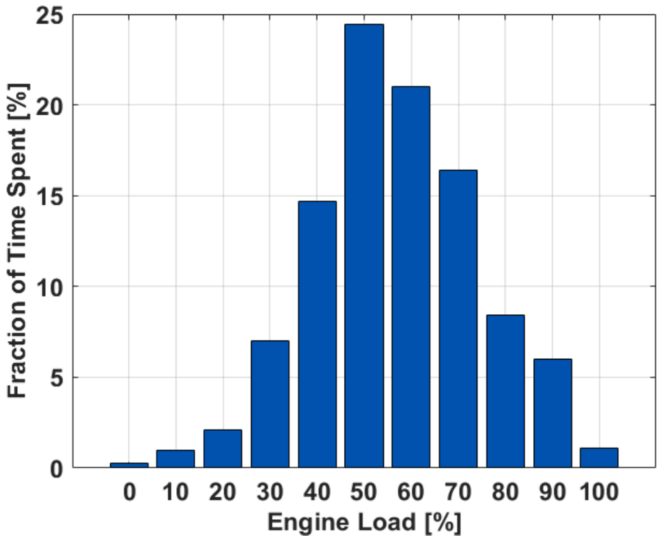

Fig. 5. Typical operational profile for a panamax container vessel [45].

3. WHR technologies classification

The non-negligible waste heat available during ship operation, highlighted in the previous section, can be valorised via waste heat recovery technologies to fulfil various on-board energetic or utility demands through conversion or transformation in the case of meeting thermal demands. WHR technologies can be classified according to the type of energy conversion, or lack thereof, performed, typically denominated as 'Heat-to-*X*' where *X* is the yield delivered by the WHR technology. These include Heat-to-Heat, Heat-to-Power [46], Heat-to-Cooling, Heat-to-Mechanical, and other technologies, which in this review include desalination, for which the payload is desalinated water rather than work. The classification and the relevant 'Heat-to-*X*' technologies are shown schematically in Fig. 6.

The technologies reviewed in this article were selected to provide an up to date and complete review of on-board WHR options, which covers all 'Heat-to-X' types, with a greater focus on innovative, novel technologies that are largely missing from current review articles on marine WHR state of the art. Technologies that are included display a high relevance for on-board applications with supporting evidence or high novelty where relevance may need investigation and therefore which warrant additional attention and quantification of performance to cross-compare with alternative WHR solutions.

The review covers the full spectrum of WHR technologies, including novel power cycles (organic Rankine, Kalina cycles) and unconventional power generation through thermoelectric generators, novel sorption-reaction-based refrigeration technologies as adsorption and absorption. Thermal energy storage is also considered given its high potential, high novelty, which has attracted attention for marine applications [47–49] and it is addressed in detail in this review. Finally, isobaric expansion engines is a very novel heat-to-mechanical power technology [50], which is reviewed here for the first time in the context of on-board WHR. The review also investigates some existing WHR technologies which can be seen as the current WHR baseline and essential for current on-board WHR: turbine-based power generation with turbocompounding and steam Rankine cycles, these technologies being commercially developed by engine manufacturers, and simple heat recovery and transfer with WHR-heat exchangers.

Heat pumps are mentioned as a technology for increasing the temperature of a storage material to fulfil the requirements of energy demand. Although these devices are widespread and well established for waste heat recovery in terrestrial applications, their use on-board vessels has not been extensively investigated in literature yet. Some existing proposals consider the possibility of utilising heat pumps in combination with ORC systems to exploit the exhaust heat and TES systems to enhance the flexibility of thermal energy supply on vessels [51,52]. This solution could have the advantages of providing both heating and cooling at the same time and ensuring higher efficiency levels than electric boilers and oil-fired boilers. In particular, the electricity consumption of a heat pump is approximately 60 % lower than that of an electric boiler [51,53].

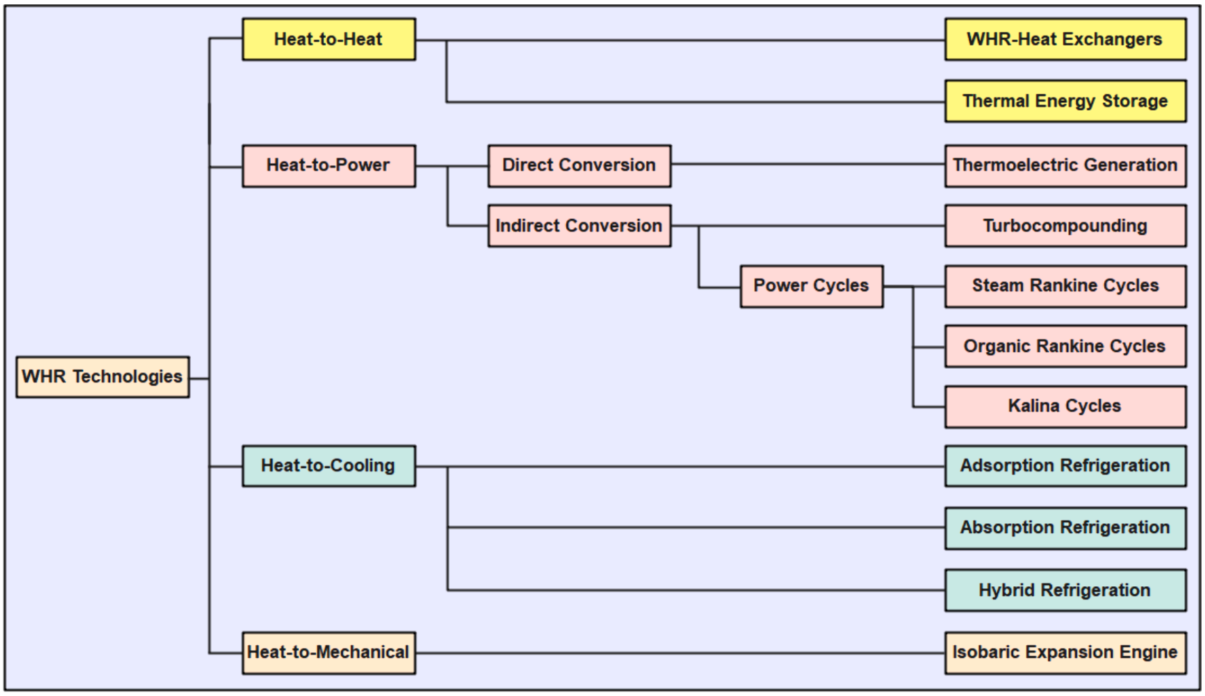

Fig. 6. On-board WHR technology classification.

4. Literature review methodology and systematic techno-economic performance indicators

4.1. Literature review methodology

The present review was conducted by consulting the academic literature and grey literature. The academic literature was consulted using the reference website Scopus [54], while the grey literature was consulted with direct search on web search engines, on research project databases, specifically the CORDIS of the European Commission [55], and the websites of Diesel marine engine manufacturers, specifically Wartsila [26] and MAN [25]. Bibliography was gathered by using various complementary search terms. The overall consulting strategy was to search for 'Waste heat recovery' and combine this term with specifications such as 'Marine', 'On-board', or 'Diesel Engine' to obtain the literature dealing with WHR specifically in ships or diesel engines. Academic and grey literature on the topics of individual WHR technologies was consulted by searching for terms such as 'On-board/Marine + <Technology name>', such as 'Thermal Energy Storage', 'Organic Rankine Cycle', and so forth for all technologies reviewed in this article. The complete list of reviewed technologies shown in Table 1.

4.2. Systematic techno-economic performance indicators definitions

The cross comparison of WHR technologies characteristics to increase their penetration into on-board energy systems requires the assessment of their techno-economic performance through specifically chosen indicators; these performance indicators are categorised into technical performance indicators pertaining to energetic performance and capability of delivering the intended payload, and economic performance indicators. Some performance indicators only pertain to specific technologies, while others can be applied to all the reviewed WHR technologies, such as specific cost.

4.2.1. Technical performance indicators

All WHR technologies are designed to generate some type of useful effect, whether it be thermal energy directly or its conversion into electrical power or cooling. The useful work is defined as the net value of the work output W_{net} [kW], and is a function of the useful work output W_{useful} of the system and other potential electrical work inputs $W_{secondary}$ to the system, such as the pumping work in any WHR cycle using a working fluid in a secondary circuit. The definition of W_{net} can be found in **equation (2)**:

$$W_{net} = W_{useful} - W_{secondary} \tag{2}$$

For most technologies, the ability to convert waste thermal energy to useful work is measured by the efficiency η [%]. This performance indicator is also commonly referred to as thermal efficiency or cycle efficiency, and is defined in **equation (3)** as the ratio between net value of the work output and the value of the input heat Q_{WH}:

$$\eta = \frac{W_{net}}{Q_{WH}} = \frac{W_{useful} - W_{secondary}}{Q_{WH}} \tag{3}$$

Exergy-based analysis, particularly in heat-to-power evaluations, offers several advantages. It considers the quality of energy, reflecting real-world conditions by accounting for irreversibilities, and provides insights into areas for improvement by examining entropy generation [56]. However, there are also some disadvantages involving the higher complexity in calculation, the limited applicability for certain systems, and the challenges in interpretation and comparison across different systems [56]. It is generally recommended to adopt a more extensive and systematic approach, aligning with terrestrial applications, to analyse and optimise procedures relevant to the maritime sector, thus correctly designing geometric and operating conditions of systems [57]. The use of the first law can be justified by a simpler framework for analysis and interpretation, which reduces complexities and challenges in the definition of the design of comprehensive systems.

For WHR cooling technologies as adsorption and absorption refrigeration systems, the ability of the technology to convert the input thermal energy to useful work is measured by the coefficient of performance *COP* [-], which, as for the efficiency, is the ratio between cooling power output Q_{cool} [kW] and input heat Q_{WH}, as shown in **equation (4)**:

$$COP = \frac{Q_{cool}}{Q_{WH}} \tag{4}$$

The primary function of desalination technologies, and the secondary function of adsorption desalination and refrigeration (**section 5.3.2**), is to produce fresh water; their performance is quantified by calculating the mass of fresh water generated per unit time. Desalination performance is measured using specific daily water production *SDWP* [kg/day], the performance metric for WH-driven desalination technologies, including adsorption cooling and desalination. SDWP quantifies the amount of desalinated water produced per operation cycle [58] as stated in **equation (5)**:

$$SDWP = N\int_0^{t_{cycle}} \frac{Q_{cond}}{\rho_w L_w m_{ads}} \tag{5}$$

Where t_{cycle} is the duration of a cycle, N the number of cycles in a day, $\dot{Q}_{cond}$ the condensation heat flux, ρ_w liquid water density, L_w latent heat water condensation, and m_{ads} the mass of adsorbent. The primary function of refrigeration technologies is producing cooling, thus the main performance indicators for such technologies is specific cooling power SCP [kW/kg]. SCP measures the ability of a device to generate cooling power and is defined by the amount of cooling power generated per unit mass of sorbent material, in the case of adsorbent or absorbent-based cooling WHR technologies. SCP is computed using **equation (6)**:

$$SCP = \frac{Q_{cool}}{m_{ads} t_{cycle}} \tag{6}$$

Where $Q_{cooling}$ is the generated cooling, m_{ads} the mass of adsorbent, or absorbent (depending on the cooling technology) and t_{cycle} the cooling cycle duration.

Energy storage density E_d [kWh/m^3] for a thermal energy storage device is the total amount of stored energy E_{stored}, which is typically measured during the discharge phase to account for both charge and discharge losses, divided by the volume of the thermal energy storage device V_{TES} as shown in **equation (7)**:

$$E_d = \frac{E_{stored}}{V_{TES}} \tag{7}$$

4.2.2. Economic performance indicators

The specific cost $C_{s,W}$ [€/kW] of a heat-to-power and heat-to-mechanical WHR technologies refers to the total cost per unit of delivered useful work. It is the ratio between the total cost of the system C_{WHR} and the rated work output W_{net}, in the case of all WHR technologies except thermal energy storage as stated in **equation (8)**.

$$C_{s,W} = \frac{C_{WHR}}{W_{net}} \tag{8}$$

In the case of heat-to-heat and heat-to-cooling WHR technologies specific cost $C_{s,Q}$ [€] is the ratio between the total cost of the system C_{WHR} and the rate of thermal energy output, either heating Q_h [kW] or Q_{cool} [kW], as written in **equation (9)**:

$$C_{s,Q} = \frac{C_{WHR}}{Q_{cool}} or C_{s,Q} = \frac{C_{WHR}}{Q_h} \tag{9}$$

In the case of TES, economic performance is conventionally measured using the storage capacity cost usually referred to as specific cost of storage (SCC), which is the ratio between the total cost of the TES device and the maximum amount of energy stored in the TES [59,60] according to **equation (10)**.

$$SCC = \frac{C_{TES}}{E_{stored}} \tag{10}$$

The specific cost was considered for evaluating the economic characteristics of the WHR systems on vessels as it allows for conducting a general analysis. Conversely, the use of another parameter as the levelised cost of energy (LCOE) would require the consideration of capital expenditure, operational expenses, maintenance costs, and, where relevant, decommission costs, which strictly pertain to the specific characteristics of the vessels and WRH technologies and their management over the entire life-time.

For technologies where installation and maintenance costs were not provided, or data was unavailable or inconsistent, it was not included in the text.

5. Results and discussion

Having defined the archetypal multi-energy system, on-board waste heat sources and demands, and defined the key performance indicators through which WHR technologies are evaluated, the following section contains the review of the individual technologies. Starting with Heat-to-Heat technologies, 11 different WHR technologies are reviewed, which are categorised according to Fig. 6, along with Heat-to-power, Heat-to-cooling and Heat-to-Mechanical WHR technologies.

5.1. Heat-to-heat

5.1.1. Waste heat recovery heat exchangers

The simplest utilisation of marine waste heat is direct re-integration into the on-board energy system to fulfil heat demands, such as domestic hot water for the crew or steam demand. A more detailed description is provided in **section 2.1** for on-board thermal demands. Direct heat recovery and reintegration is commonplace in a number of terrestrial applications such as combined heat and power plants, waste-to-power plants and various industrial processes [61]. Waste Heat Recovery Heat-exchangers (WHR-HX) are used to capture and redirect excess heat resources – their main technical requirement in this case is the temperature compatibility between the source and demand. Since various types of WHR-HX technologies have seen applications for terrestrial WHR and in other energy intensive processes, they are also relevant to on-board energy systems and included in this review.

Heat exchangers are commonly used for basic WHR operations. The simplest WHR method for on-board energy systems that can be envisioned is integrating a WHR-HX after the engine turbochargers to recover waste heat available in the exhaust gases. The choice of WHR-HX then depends on the properties of the waste heat stream and the intended use of the recovered heat. Five WHR-HX technologies can be highlighted for vessel WHR [18]:

- **Economisers** are low to medium temperature finned tube heat exchangers used to preheat boiler feedwater for steam generation and reduce fuel expenditure in boilers.
- **Waste Heat Boilers** are medium to high temperature heat exchangers designed to generate steam.
- **Recuperators** are medium to high temperature heat exchangers with air being heated on the WHX cold side.
- **Regenerators** are heat exchangers where hot and cold fluids alternately flow in the same common channel which contains a ceramic or refractory material.
- **Heat Recovery Steam Generators** (HSRG) are multiple pressure level heat exchanger systems designed to generate high pressure steam.

Scientific literature and grey literature provide a limited number of studies focusing exclusively and solely on WHR-HX for marine applications. However, analysis of the on-board WHR literature shows that HX are commonly used as parts of WHR technologies relevant for on-board applications. For instance, steam-turbine based WHR technologies as turbocompounding (**section 5.2.1**) make use of these heat exchangers. One or two pressure level waste heat boilers are used for steam turbine cycles [63], while exhaust gas economisers are used in some WHR devices such as the waste heat recovery plant layout from Winterthur Gas & Diesel [64]. In this latter case, exhaust gas exiting the turbochargers flows through a power turbine (direct exhaust gas driven turbine), before passing through an exhaust gas economiser to produce steam; part of the steam flows through a steam turbine, and the other part is sent to the steam services of the ship. The turbocompounding system from MAN Diesel & Turbo makes use of a multi-pressure level HRSG, complete with preheater, evaporator and superheater sections [65]. Regenerators find use in the isobaric expansion engine (**section 5.4.1**) to store heat between piston strokes [66]. Recuperators can be used in modified Rankine cycle (**section 5.2.2**) or Kalina cycles (**section 5.2.3**) for on-board WHR as a means to increase cycle efficiency [67,68].

Relevant WHR HX technologies for marine applications have only briefly been discussed here, since the scope of this article, as previously emphasized, is primarily on novel, innovative, and emerging WHR technologies. Nonetheless, available review papers and works from the grey literature which extensively deal with WHR-HX technology as shown in Table 3. Thus, rather than fully addressing each WHR-HX technology in detail in this review, the main benefits, drawbacks, and reference literature which contains extensive discussions for the five discussed WHR-HX technologies are summarised in Table 3. It can briefly be mentioned that these technologies are proven and have for the most part multiple available commercial solutions. Economisers, waste heat boilers and HSRG must specifically be paired with a steam system, while recuperators and regenerators can redirect heat to any application.

5.2. Heat-to-power

5.2.1. Turbocompounding

Turbocompounding consists of a turbine to convert waste heat from the exhaust gases of an engine into electricity; it is from the point of view of an engine manufacturer the one of the primary waste heat-to-power technology [10,69]. According to MAN, turbocompounding systems is an established WHR technology with TRL9 that is easily retrofitted on existing ships [20]. In some publications turbocompounding is referred to as exhaust gas turbine systems [70]. Turbocompounding systems are designed according to three possible configurations, power turbines

Table 3
Characteristics and reference literature for WHR-HX.

	Advantages	Drawbacks	Temperature Range	Refs
Economiser	Proven technology Increases boiler efficiency. Resistant to fouling	High heat transfer areaRequires steam system	120 °C – 300 °C	[18,61,62]
Waste Heat Boiler	Proven technologySteam generation	Only for steam generation Insufficient when aloneBulky equipment	300 °C – 1000 °C	[18,61,62]
Recuperator	Proven technology	Fouling issues from HT EG	Low-High	[18,61]
Regenerator	Proven technology	Fouling issues from HT EG	Medium-High	[18,61]
HRSG	Steam generation	Requires steam system	High	[18]

Table 4
Installation and maintenance costs for different types of turbocompounding WHRS [77] with costs actualized and converted from dollars to euros.

	$C_{s,W}$[€/kW]	Maintenance Costs [€/year]
PTG	105	10,500
STG	320	21,000
ST-PT	420	32,000

generators (PTG), steam turbine generators (STG) and combine power turbine and steam turbine (ST-PT), which are shown schematically in Fig. 7 [10,71].

5.2.1.1. Power turbine generator (PTG). Exhaust gas flows through a so-called power turbine connected to a generator via a gearbox to generate electricity for a 3 % to 5 % potential recovery ratio. A bypass valve is installed to transfer 8 % to 12 % of the exhaust gases directly to the PTG without passing through the turbocharger. PTG is typically selected in instances where the total main engine power below 15 MW.

5.2.1.2. Steam turbine generator (STG). In an STG system, an exhaust gas fired boiler is used to generate steam which flows through a steam turbine to produce electricity, for a 5 % to 8 % potential recovery ratio. The steam flow is then condensed, pumped, and returned to the boiler. STG is typically installed in instances where the main engine power rating is between 15 MW and 25 MW. It is generally referred to in energy systems engineering as Steam Rankine Cycle (SRC), which is the conventional thermodynamic cycle when using a steam turbine and has been designed for power generation ranging from ~ 50 kW to several hundreds of MWs [46]. The steam generation devices needed on-board to operate an STG system tend to be either as single pressure or dual pressure systems, with recommendations from MAN for the STG steam systems pointing towards a 10 to 11 bar for the HP steam and 3 to 4 bar for the LP steam in the case of the dual pressure system, and ~ 7 bar steam for the single pressure system. The cycle requires a heat source at temperatures above 300 °C, in order to generate and superheat steam at high pressures above 15 bar [24,72]. Superheating is necessary to protect turbine blades from condensate droplets causing mechanical damage by erosion.

5.2.1.3. Steam turbine and power turbine (ST-PT). This system combines the operating principle of the previously described STG and PTG in a single device, with a power turbine and a steam turbine connected to the same generator shaft, for an 8 % to 11 % potential recovery ratio [64]. The combined ST-PT system should be installed on vessels with main engine power ratings above 25 MW. A complete diagram of the ST-PT system with dual-pressure steam device is provided in Fig. 8. In both the STG and ST-PT systems, a small amount of exhaust gas between about 8 % and 12 % of the total flow bypasses the main engine turbochargers to increase the temperature of the exhaust gas flow at the inlet of the EFB to produce higher quality steam and operate the whole system more effectively [20].

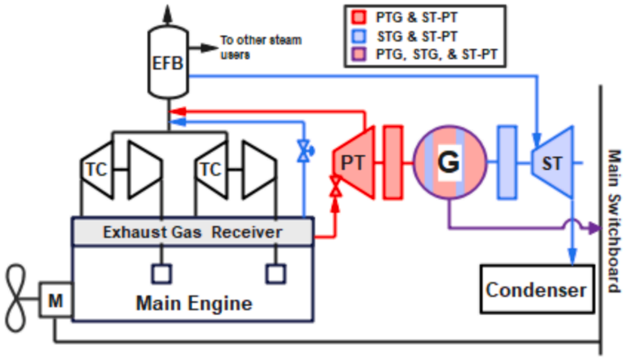

Fig. 7. Schematic representation of turbocompounding WHRS PTG system, STG system and combined ST-PT system.

5.2.1.4. On-board integration. A ST-PT system was developed by Wartsila [73], which was able to recover approximately 10 % of a 68,640 kW rated Sulzer 12RT-flex96C power at 100 % SMCR as electricity. This device features a dual pressure steam turbine, high pressure at 9 bar, and low pressure at 3 bar, running at 6,750 rev/min reduced to 1800 rev/min via gearbox. Mitsubishi Heavy Industries [74] have also manufactured ST-PT turbocompounding systems with a Mitsubishi ATD52CLM 2,500 kW rated steam turbine and 1,700 kW rate power turbine, recovering 7 % – 9 % power from a 47,740 kW engine at total SMCR. Theoretical results from simulations carried out by Ma et al. point towards similar results of approximately 10 % maximum engine power recovered as electrical power at 100 % SMCR [23]. A picture of a combined ST-PT system as designed by MAN is shown in Fig. 9.

STG systems can integrate to the on-board energy system in the simplest way by powering a steam boiler directly with exhaust gases to produce steam in a closed loop for the cycle. Through a thermodynamic analysis, it was estimated by Senary et al. [72] that at 100 % SMCR an integrated 17 bar basic layout SRC (steam superheated to 280 °C) could improve fuel efficiency by 8 %, using only waste heat from exhaust gases to preheat, boil and superheat water. Vanttola and Kuosa [24] found that the integration of an STG on a bulk carrier could lower fuel consumption by 5 %. It is sometimes suggested to combine the multiple waste heat sources in series to evaporate the working fluid. Larsen et al. [68] compared various power cycle options for on-board WHR, and suggested preheating water in a dual pressure system between 3.4 and 9.8 bar connected to STG using the jacket cooling water and charge air before performing the evaporation with the exhaust gases, improving fuel efficiency by 1.7 %. Liang et al. [75] analysed thermodynamically an STG coupled to an ammonia-water absorption refrigeration system. Water is preheated with jacket cooling water, and then evaporated into steam and superheated with heat from the exhaust gases (325 °C). The two devices were coupled by using the heat of condensation as a heat source to evaporate ammonia for the refrigeration system. Total cycle efficiency of 19 % was calculated.

The net power output of a turbocompounding WHRS depends on the main engine load which can vary significantly during a single voyage [76], since available waste thermal power is proportional to the main engine load. The expected performance of a ST-PT turbocompounding WHRS as a function of main engine load is shown in Fig. 10, which features data from literature [10,23,73,74]. Combined ST-PT are the most complex and efficient type of turbocompounding system; thus, this graph shows the upper bound of the expected performance of such devices. In practice, steam turbines in STG and ST-PT systems are only operated for engine loads above 30–35 % SMCR, and power turbines in PTG and ST-PT systems for engine loads above 40–50 % SMCR. Below this engine load, the exhaust gas bypass valve is kept closed. This operating practice explains the steep drop in WHRS performance at lower loads seen in Fig. 10.

Table 2 shows typical installation and maintenance costs for the different types of turbocompounding system. The data was synthesised by Olaniyi and Prause [77] from various turbocompounding WHRS manufacturers such as MAN [10] or Wärtsilä [73].

5.2.2. Organic Rankine cycles

The process diagram of a conventional Rankine cycle in its most simple layout, using main engine exhaust gas as the heat source, is shown in Fig. 11. Thermal energy from the exhaust gases is used to evaporate a working fluid in the evaporator (1 to 2). The working fluid vapour is expanded to the low-pressure level of the cycle in a turbine to produce useful work (2 to 3) that is converted to electricity in a generator. The working fluid is then condensed (3 to 4) before being pumped

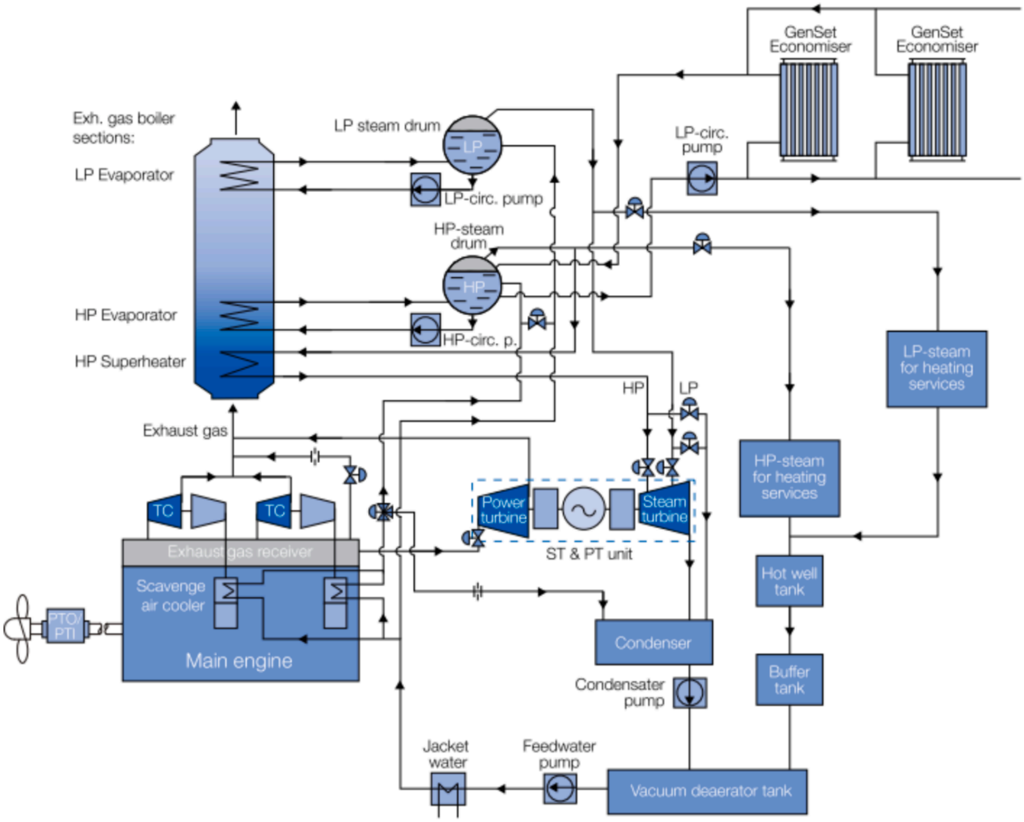

Fig. 8. Exemplary diagram of the combined ST-PT system developed by MAN [10].

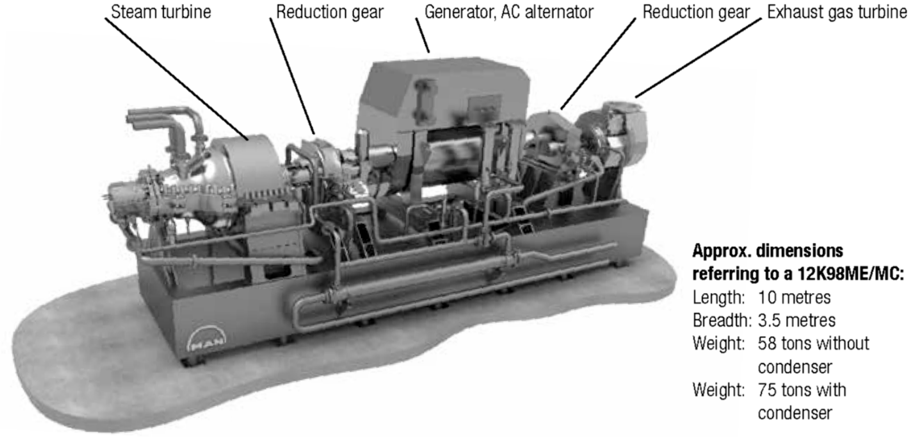

Fig. 9. MAN combined ST-PT system [65], where can be seen the main features: steam and exhaust gas turbines on the same shaft, with generator and reducing gearbox.

to the higher-pressure level of the cycle (4 to 1) into the boiler, completing the process. Some typical modifications to the cycle to increase performance include recuperation, bleeding, and the use of multiple loop cycles [78]. In recuperative cycles, residual heat in the working fluid at the turbine exit is used to preheat the same working fluid at the entry of the evaporator, boiler, or heat source. Multiple loop cycles are aimed at maximising efficiency by utilising two or more separate working fluid flow loops, differentiated by their different pressure levels, to extract heat from as many different heat sources. In bleeding cycles, part of the working fluid flow is extracted to preheat the flow at boiler entry and is then circulated into a lower pressure secondary Rankine cycle loop.

ORCs have been extensively studied in the scientific literature for both conventional and marine WHR [57,79,80]. A 100 kW ORC with multiple temperature level heat sources from various waste heat streams, including using jacket cooling water for preheating was investigated by Song et al. [81]. A similar concept was studied thermodynamically by Lion et al. [82]. Various configurations, aimed at vessel WHR and attempting to fully leverage the archetypal on-board waste thermal energy sources (such as using HT cooling water for working fluid preheating), were modelled by Casisi et al. [83]. Outside of the scientific literature, the conventional ORC, aimed towards biomass, CHP, geothermal and industrial WHR, is traditionally manufactured by constructors such as Ormat, Turboden and GE [84,85]. However more recently ORC modules specifically designed for on-board energy systems have become market ready: Orcan-Energy’s *Efficiency*

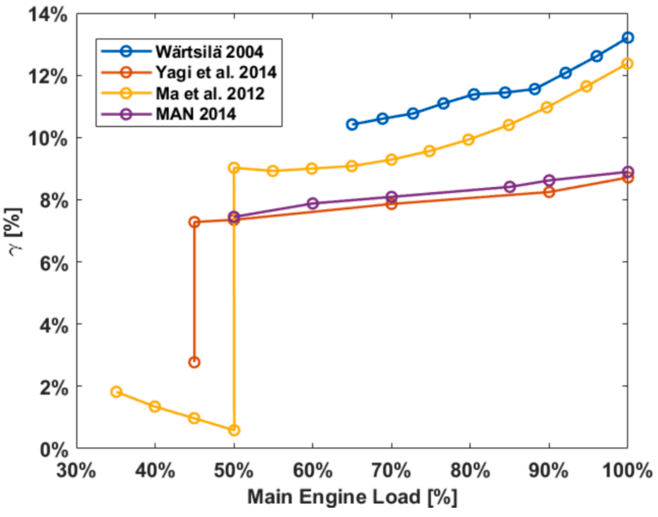

Fig. 10. Turbocompounding ST-PT WHRS heat recovery ratio as a function of main engine load.

Pack [86], Alfa Laval's *E-Power Pack* [87], or the Caltenix Mitsubishi partnership's *Hydrocurrent TM Organic Rankine Cycle Module 125EJW* [88,89] are illustrative examples. The performance of some ORCs aimed at marine WHR is shown in Table 5 (For Kalina Cycles See Tables 6 and 7).

As shown in investigations in Table 5, it appears that analysis of the on-board applications of ORC devices systematically report thermal efficiency relying on **equation** (3) while more rarely and inconsistently exegetic efficiency is also ascertained.

Economic performance of both marine ORCs and conventional WHR ORCs is shown in Fig. 13, measured through specific cost $C_{s,W}$. The economic data indicates an economy of scale, where larger ORC systems have lower specific cost. Furthermore, a comparison of on-board system with other applications shows that these cost estimates (blue datapoints) are in line with terrestrial ORC system costs, pointing both towards a reasonable accuracy of the theoretical estimation of naval ORC costs, and that terrestrial ORC economics are representative on-board ORC economics. On-board ORC devices with net power output in the range 100 to 1,000 kW display system costs around 10,000 €/kW to 5,000 €/kW, respectively.

Despite their deployment in conventional waste heat recovery (WHR) contexts, ORC systems have not yet been suitably adapted for marine applications. The main challenges to overcome include conducting research to specifically design these devices for vessel operations, testing the related prototypes, integrating them in the vessel energy system, reducing capital expenditure, and complying with maritime regulations [57,79,80].

5.2.3. Kalina cycles

Kalina cycles are low-temperature power cycles, designed as an alternative to the Rankine cycle, based on evaporating and expanding in a turbine an ammonia-water mixture to generate electrical power [97–99]. Ammonia-water is a zeotropic mixture and the boiling point of the mixture is dependent on the mass fractions of the components of the mixture; thus Kalina cycle can be designed to best match a naturally intermittent heat source such as engine exhaust gas [100]. While a wide range of theoretical thermodynamic studies and simulations have been carried out, very few actual installations exist.

A schematic representation of the Kalina cycle process in the context of marine exhaust gas WHR is shown in Fig. 12. Waste heat from the main engine exhaust gas is used to evaporate the ammonia-water zeotropic mix in the boiler. Working fluid vapour then flows through an expander connected to a generator, yielding electrical power transferred to the vessel main switchboard. The mixture at the outlet of the turbine exchanges residual thermal energy with the flow upstream of the boiler in recuperator R1, before being condensed with seawater or another coolant and pumped to a higher pressure level in pump 1. The mixture is separated in two streams (splitter Sp), with one part being preheated by the turbine outlet in recuperator R2 and flash separated in Se. The ammonia-rich vapour phase is mixed with the second stream exiting splitter Sp to enrich the working fluid, while the weak ammonia phase is mixed in M1 with the turbine outlet after the two recuperative heat exchangers R1 and R2. The enriched solution is pumped again to a higher pressure level (pump 2), before being preheated by the turbine outlet in R1 and entering the boiler, thus completing the cycle. Despite the original objective, the Kalina cycle is technically more complex than the conventional Rankine cycle with multiple separators and an additional pump required, which could explain the lack of actual implementations.

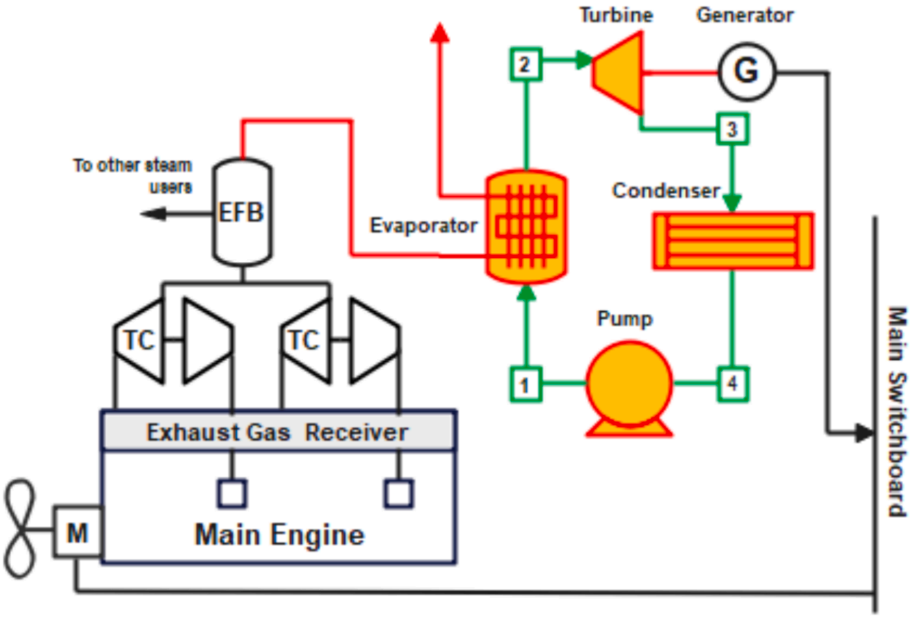

Fig. 11. Schematic representation of a Rankine cycle WHRS using main engine exhaust gas as heat. EFB: Exhaust Gas Fired Boiler.

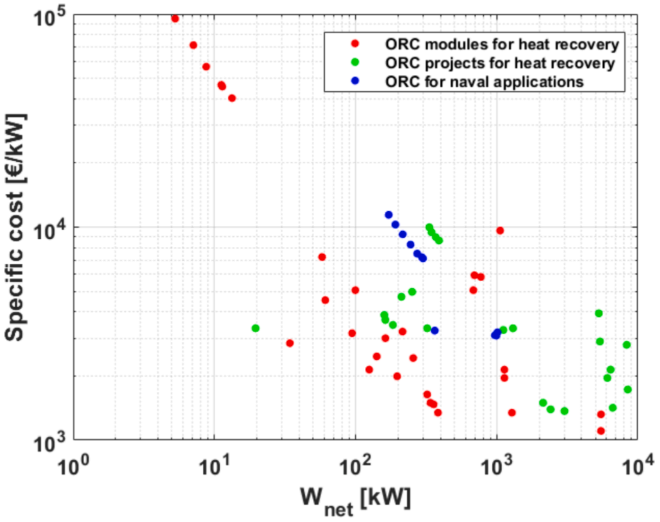

Fig. 12. Specific cost $C_{s,W}$ of ORC installation as a function of net power output, for ORCs designed for on-board energy systems [83,91,92], along with ORC (modules and large projects) costs for conventional WHR [96].

The diagram shown in Fig. 12 presents a Kalina cycle using a single waste heat stream. However, this cycle can valorise multiple waste heat streams at different temperature levels due to the zeotropic nature of the working fluid. For instance, the fluid can be preheated using engine cooling circuits before being evaporated using waste heat from the exhaust gases [101]. Characteristics and performance of various Kalina cycles designed for WHR are shown in Table 4. This table shows only data from theoretical literature studies as actual Kalina cycle implementation is nearly non-existent [102]. From this table can be noted the wide range of heat source temperatures, from 98 °C to 566 °C, despite the unique working fluid, and range of net work outputs, from 21.7 kW to 8,600 kW. Overall plant efficiency appears to scale with plant size and is similar to Rankine cycle efficiency between 7.5 % and 35 %.

To fully use Kalina cycle capability, Larsen et al. [116] propose a unique variant of the Kalina cycle called split-cycle, in which the ammonia concentration of the working fluid can be modified during the cycle. Concentration variation is achieved by introducing an additional set of mixers and splitters to the process. This additional equipment requires additional installation space on board. The authors also mention benefits of Kalina cycles linked to the working fluid; ammonia is already used in some catalytic reduction installation on-board and presents lower environmental risks than other refrigerants and working fluids used in ORCs or some refrigeration cycles. Feng et al. [117] suggested combining the Kalina cycle to a supercritical CO_2 Brayton cycle. In this study heat is supplied to the Kalina cycle at constant temperature 270 °C, and power output was measured between 1000 and 2000 kW with energy efficiency from 30 % to 45 %, respectively for ammonia mass concentrations between 30 % and 80 %. Kalina cycle costing elements, for a range of plant capacities and applications, are shown in Table 5, and inversely scale with plant size, ranging from 1,000 to 1,500 €/kW above 1 MW to 2,000 €/kW to 3,000 €/kW for systems below 500 kW. Several authors from the previous studies expect the main heat exchanger (evaporator) connecting the heat source to the cycle to be an expensive component.

Kalina Cycles for on-board applications are still at the research and development stage. Subsequently, prototypes need to be created and tested to ensure reliability and efficiency under maritime conditions. The lack of experimental tests on prototypes is currently the main challenge to overcome It is also essential to define the seamless integration with existing ship systems, reduce capital expenditure and operational costs to make the technology economically viable for shipowners, and meet maritime regulations and standards for safety, environmental impact, and performance [97,98].

5.2.4. *Combined supercritical CO_2 cycles*

Combined supercritical CO_2 cycles are the object of research for heat recovery on ships due to their high efficiency in exploiting sources with high levels of temperature. The layout comprises a supercritical carbon dioxide recompression cycle and a supercritical carbon dioxide regenerative cycle for recovering the waste heat of a marine gas turbine. The former acts as the topping cycle of the system while the latter acts as the bottoming cycle. Combining the two cycles allows for the reduction of the temperature of the exhaust fluid at its exit to maximising the exploitation of its energy. In particular, the majority of waste heat is recovered by the topping cycle which provides an exhaust fluid with a low temperature to the bottoming cycle which regeneration the remaining heat [118]. Thus, comparing the maritime applications of combined supercritical CO_2 cycles with industrial ones, the system layout replaces an ORC device with a supercritical carbon dioxide cycle that is more compact and compliant with space restrictions on-board vessels [119]. Combined supercritical CO_2 cycles for vessels are currently in the research and development phase. Consequently, fundamental research is initially required to develop systems specifically tailored for marine environments, considering the unique operational conditions and space constraints on ships [119].

Table 5
Technical performance of marine ORCs.

Heat Source Temperature [°C]	Layout	Working Fluid	Net Power Output [kW]	Efficiency [%]	ExergeticEfficiency	Study Typology	Ref
82.8 / 51.9	Basic	R-245ca	427	7.39	Not quantified	Theoretical	[21]
300 / 90	Dual Heat Sources	Cyclohexane	96	20.75	Not quantified (only exergy destruction)	Theoretical	[81]
300	Parallel ORCs	R245fa	101	10.20	Not quantified (only exergy destruction)	Theoretical	[81]
190	Regenerated	Toluene	482	20.90	Not quantified (only exergy destruction)	Theoretical	[76]
293.15	Regenerated	Benzene	396	22.00	Not quantified	Theoretical	[90]
315	Basic	R123	625	16.38	Maximum around 40 %	Theoretical	[91]
Up to 550	–	–	150	~10–20	Not quantified	Commercial	[87]
160	Basic	R236fa/R245fa	994	8.43	Not quantified	Theoretical	[92]
300 /90	Dual Loop	Water (HT) / R236fa (LT)	115	11.60	Maximum around 20 %	Theoretical	[93]
80	Basic	R245fa	125	6.20	Not quantified	Prototype	[88,89,94]
145	Regen.	Toluene	684	26.70		Theoretical	[83]
240 / 140 / 89 / 65	4 Heat Sources ORC	R134a	3399	41.10	Not quantified	Theoretical	[35]
207 / 97	Dual loop	Wet steam (HT) / R236fa (LT)	115	11.95	Not quantified	Commercial	[95]

Table 6
Characteristics and performance of WHR Kalina cycles, data originally synthesized in [102].

Heat Source	$T_{heat\ source}$ [°C]	Power [kW]	η_{th} [%]	Ref
Gas flow from oxygen conversion	98	3,450	10.4	[103]
Vapour flow	116	3,300	7.6	[104]
Clinker exhaust gases and cooling	360	8,600	–	[105]
Clinker cooling	–	4,750	–	[106]
Vapour flow	179	1,362	20	[107]
Thermal oil	200	278	11.7	[67]
Generic industrial heat source	300	739	21.7	[108]
Coal combustion flue gas	150	320	12.3	[109]
Cement preheater exhaust gases	390	3,430	23.3	[110]
Engine exhaust gases and cooling	524 / 86.8	21.7	25.6	[101]
Engine exhaust gases	439	217	18.8	[111]
Engine exhaust gases	346	1,615	19.7	[112]
Gas turbine exhaust gases	566	3,137	28.6	[99]
	550	–	30	[113]
	522	86,136	35.6	[114]
	550	–	30.7	[115]
	560	2,700	32.9	[98]

Table 7
WHR Kalina cycles costing elements, data originally synthesized in [102].

Application	Capacity [kW]	$C_{s,W}$[€/kW]	Year	Ref
Geothermal	< 500	2,000 – 3,000	2009	[109]
Geothermal	1,850	1,150	2013	[120]
Cement Plant	6,000	1,500	2005	[121]
Gas Turbine Bottoming Cycle	86,000	1,157	1991	[114]

5.2.5. *Thermoelectric generation*

Thermoelectric generation (TEG) is a technology that directly generates electricity from heat by means of the Seebeck effect, which is that a temperature difference in two connected semi-conducting materials results in a voltage difference. The connection is made with a gold or nickel strip [122]. The magnitude of the voltage gradient depends on the magnitude of the temperature difference, thermo-electric properties of the semiconductors and of the metallic strip [123]. The TEG principle is shown schematically in Fig. 14, cost of TES in Fig. 15.

TEG is a typically investigated technology for industrial WHR [124,125], interest which has spread to Diesel engine WHR [126] and for on-board energy systems [37]. TEG is at a technological readiness level where various commercial devices are available, their techno-economic performance being shown in Fig. 16. The main drawbacks of TEG are low heat-to-electricity conversion efficiencies below 5 % and volumetric power output. Most commercial systems are clustered in the 0 to 10 kW/m^2 surface specific power generation range, except for one brand.

In Fig. 17 and Fig. 18 can be seen two examples TEG designs, targeted specifically towards marine waste heat recovery from on-board

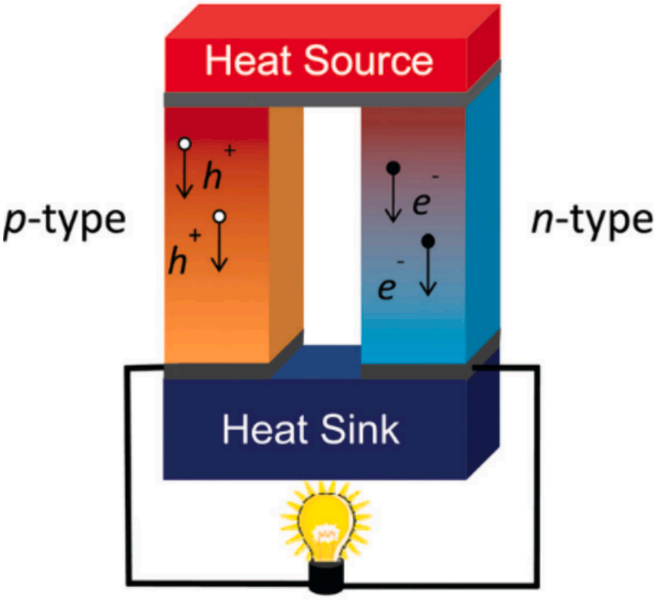

Fig. 14. Schematic representation of the TEG concept [123].

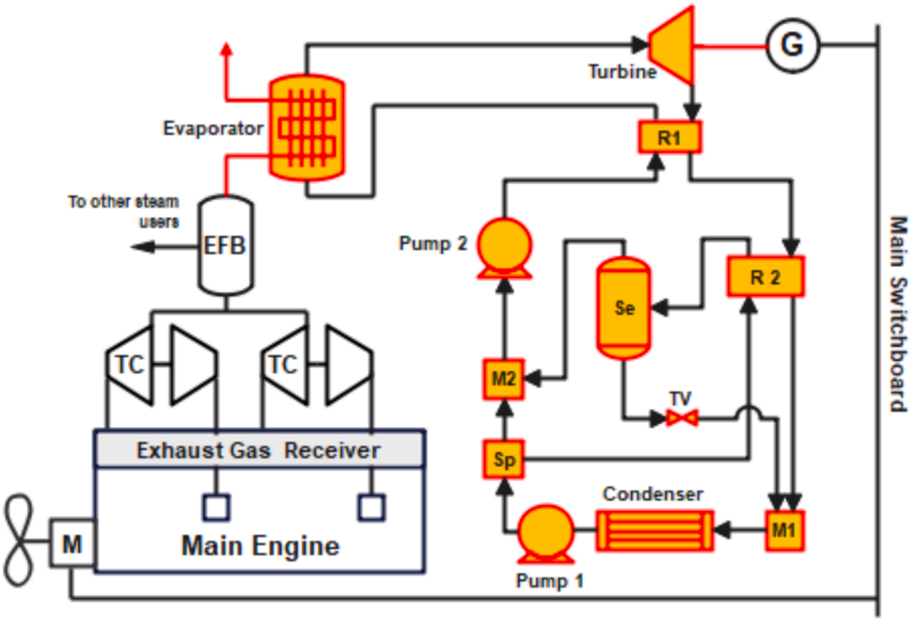

Fig. 13. Schematic representation of a Kalina cycle WHRS using main engine exhaust gas as heat process features recuperator heat exchangers (R1 and R2), mixers (M1 and M2), a separator (Se), a splitter (Sp) and as throttle valve (TV).

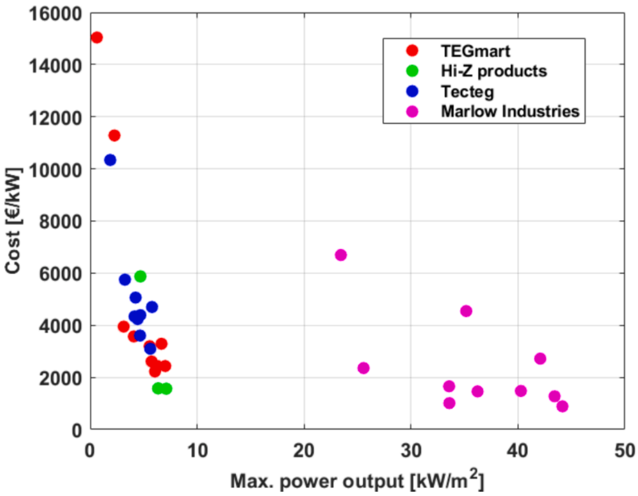

Fig. 15. Commercial TEG modules techno-economic performance, measured by specific cost $C_{s,W}$ as a function of maximum power output [127–130].

waste incinerators, a type of on-board waste and pollution management device that operates at temperature range 850—1200 °C with exhaust gases that are typically cooled down to below 350 °C. The TEG in Fig. 17 was designed to be placed in the flue gas outlet channel, all while being cooled with sea water with a temperature between 5 °C and 30 °C as heat sink. The flue gas channels can clearly be seen in the design; it is intended to be placed lengthwise in the flue gas containing pipe in the direction of the flow. Due to flue gas corrosiveness the device is made of stainless steel 316 with an outer layer of copper for better heat distribution that is the 'thermal spreader' of Fig. 17. The device is modular so that an ideal number of modules can be arranged together. Various designs were optimised according to either maximum efficiency, maximum net power output or minimal specific cost as the design objectives. Power outputs were between 27.4 kW_e and 57.7 kW_e, resulting in specific costs between 2.46 $/$kW_e$ and 7.42 €/kW_e respectively.

The TEG shown in Fig. 17**a** and Fig. 17**b** is designed to be placed around the inner surface of the flue gas channel of a waste incinerator, as shown schematically in Fig. 17**c**. The device has length of 500 mm, 100 mm inner diameter and 6 mm thickness. The entire system is composed of 42 such devices arranged as a hexahedron. The device achieved 882 We electrical power output, resulting in an efficiency of 4.32 %.

As the example discussed in the previous paragraph, arrays of TEG modules could be deployed across the inner surface of the ship hull below the water line [133]. This inner surface is at a temperature below 30 °C most of the time, which could lead to reasonable efficiencies for the TEG modules when considering the temperature difference with onboard waste heat sources, the lack of pumping requirements, and the sea being an infinite heat sink which is one the main drivers for TEG investigation for ships [134]. Another advantage of TEG is its ability to harvest difficult to capture waste heat, such as radiation from machinery; TEG array must simply be affixed to machinery surface. Compared to other WHR technologies which have moving parts and operating fluids and pipes, TEGs are easier to install and maintain on vessels. Currently the main factor that is limiting the development of TEG is the high specific cost of the best performing materials [123]. The high cost, the low efficiency and energy density, together with the need for extensive construction and retrofitting for the use with the main exhaust gas channel make this technology currently unattractive.

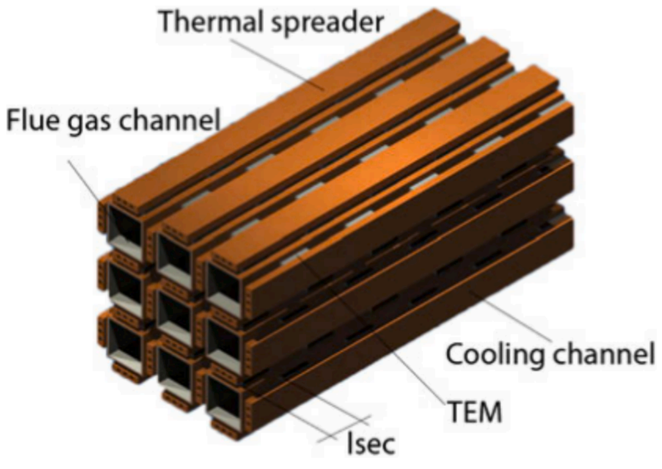

Fig. 16. Example of a TEG heat exchanger [131].

5.3. *Heat-to-cooling*

Ships provide the most cost-effective way of transporting perishable goods over long distances. Products such as fruit, fish or meat typically require controlled temperatures. Vapour compression systems were for a long time the dominant refrigeration solution aboard reefer ships as refrigerated cargo ships, particularly with R22 as refrigerant [135]. However, these are gradually being phased out in favour of more environmentally friendly solutions, which (a) use different refrigerants, (b) require less electrical power, and crucially in the context of this review (c) can be thermally driven. The following section reviews Waste Heat-to-Cooling technologies for maritime applications.

5.3.1. *Absorption refrigeration*

Absorption refrigeration systems rely on the low boiling point of a refrigerant working fluid such as ammonia to remove heat from another fluid. A so-called single stage absorption refrigeration system is represented schematically in the marine WHR context in Fig. 18. During the refrigerant evaporation process, heat is removed from a secondary fluid, typically water, which temperature is lowered to chilling or even subzero temperatures, resulting in the desired refrigeration or cooling effect. The refrigerant vapour is then absorbed by a liquid solution and pumped to a higher pressure into the generator. Thermal energy is then used in the generator to desorb the ammonia from the solution into a new, enriched vapour phase. This desorption process is the WHR stage of the cycle. The enriched vapour phase is condensed, with water as the cooling medium, and returned to the evaporator, thus completing the cycle. In the context of marine WHR, waste heat is used to heat water which is in turn used to regenerate the refrigerant solution. Seawater is used as the cooling medium in the condensation process.

Absorption refrigeration differs from the traditional refrigeration method, conventional vapour compression systems, for two reasons [136]. The first is that the refrigerant is absorbed into a liquid phase, resulting in the need for a pump rather than a compressor, which significantly reduces electrical energy requirements. The second is that the refrigerant is extracted from the liquid solution by desorption which is a thermally driven process. The single stage absorption refrigeration device has been described so far in this section; in practice several modifications are made to the cycle to improve performance. These include double stage system, cascade systems, using hybrid absorption and compression cycles, or a combination. The performance and characteristics of absorption refrigeration are shown in Table 8.

Commercial absorption refrigeration units are available; however, integrations on-board vessels are still being investigated by researchers. Various studies have been conducted using thermodynamic models [33,152–155]. The operating conditions assumed by different authors are homogenous and lead to similar performance predictions, which are summarised in Table 9. Mostly NH_3/H_2O pairs are sued, but also water with inorganic salt solutions, such as LiBr. Condensation is generally performed between 20 °C and 40 °C using seawater as thermal sink, absorption at 25 °C-30 °C with on-board freshwater, and waste heat is provided at temperatures around 80C-120 °C to the generator via a

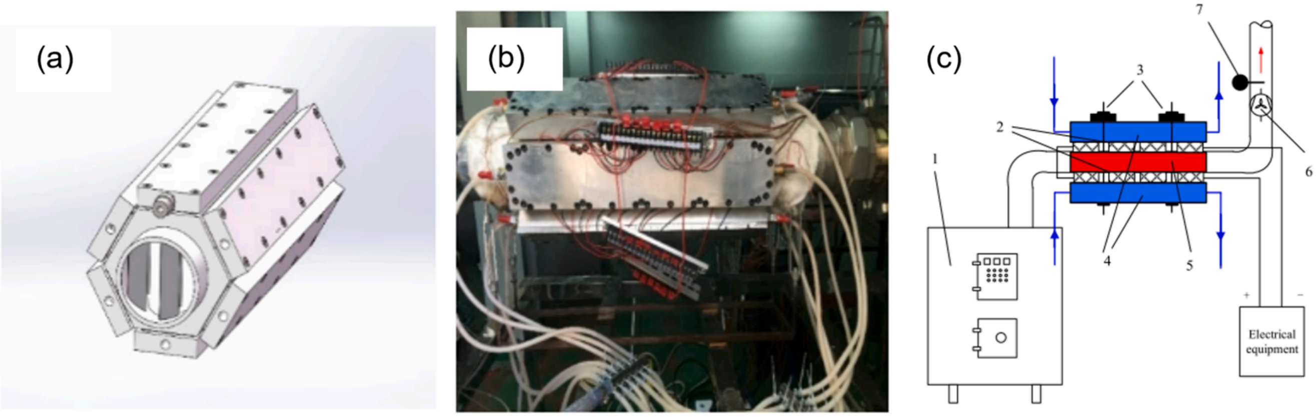

Fig. 17. TEG designed for recovering waste heat from ship incinerator exhaust gas [132]: (a) CAD design, (b) actual experimental device, (c) integration concept to incinerator, TEG module is in blue and flue gas channel in red.

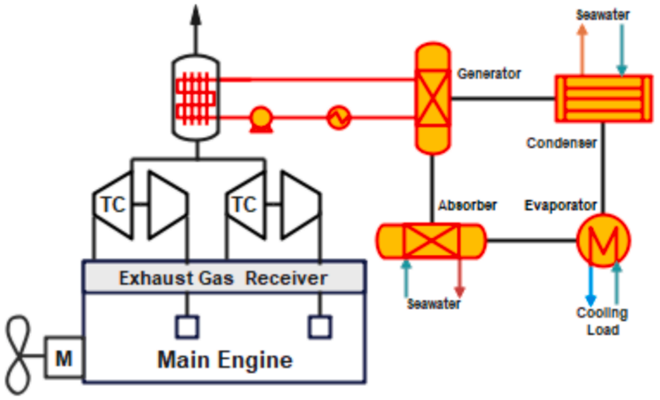

Fig. 18. Schematic representation of an absorption refrigeration cycle WHRS using main engine exhaust gas as heat source.

Table 8
Characteristics and performance of absorption cycles, data originally synthesised in [137].

Cycle	T_{evap} [°C]	COP	Working Fluid	Ref
Single stage	– 30 to 5	0.25 – 0.55	$NH_3 – H_2O$	[138]
	– 18 to 3	0.49 – 0.58	$NH_3 – H_2O$	[139]
	/	0.066 – 0.093	$NH_3 – LiNO_3 – H_2O$	[140]
	– 10	0.6	$NH_3 – H_2O$	[141]
	– 30 to 10		$NH_3 – H_2O$	–
Double-stage cascade	– 20 to 0	0.17 – 0.31	$H_2O – LiBr$ // $NH_3 – H_2O$	[142,143]
	– 20 to 0	~0.25	$NH_3 – H_2O$ // $NH_3 – LiNO_3$	[144]
	– 70 to –30	0.20 – 0.65	$NH_3 – H_2O$	[145]
	– 45	0.25	$NH_3 – H_2O$ // CO_2-NH_3	[146]
Double stage	– 15 to 0	0.32	$NH_3 – LiNO_3$	–
	/	0.29	$H_2O – NH_3$	[147]
	– 15	0.27	NH_3 – NaSCN	–
	/	0.27	$NH_3 – LiNO_3$	[148]
Absorption / Compression	– 10	1	$NH_3 – H_2O$	[149,150]
	– 50	0.58	$NH_3 – H_2O$	[151]

series of heat exchanges. A shown in the table, coefficient of performance COP around 0.5 to 0.7 can be expected for these on-board integrated systems. Cooling temperatures around −5°C are typical, while cooling power largely depends on the engine power rating and load. Salmi et al. produced 200 kW to 1200 kW cooling power with the H_2O/LiBr pair and 200 kW to 700 kW with the NH_3/H_2O aboard a bulk carrier [33]. While most studies investigate the use of exhaust gas powered desorption, Táboas et al. [153] also obtained COP 0.5–0.6 with heat from jacket cooling water at 85 °C using the $NH_3/(H_2O + LiNO_3)$ pair which evaporates at lower temperature than the ammonia water pair, reaching −17.5 °C evaporation temperatures. Absorption refrigeration costing elements are presented in Table 10.

Absorption refrigeration is already utilised in traditional WHR systems. Applying this technology on board vessels necessitates the development and testing of prototypes under marine conditions. Additionally, it is essential to ensure integration with existing ship systems, minimise capital expenditure and operational costs, and comply with maritime regulations [152,153].

5.3.2. Adsorption refrigeration and desalination

Desalination technologies are electrically, mechanically or thermally driven [157]. Thermally driven desalination methods as multistage flash desalination (MSF), the workhorse of desalination industry [157], and multiple effect desalination (MED) are traditionally the dominant technologies, particularly in merchant ships [36]. However, high energy demands from the latent enthalpy of the water evaporation process has favoured the development of alternative desalination processes, including in on-board energy devices. Nowadays, modern passenger ships, which are the type of ship with the highest freshwater demand due to high number of passengers, use reverse osmosis for desalination. This device functions by filtering high pressure water through a semi-permeable membrane and is electrically driven. Another emerging, technology that can provide freshwater from a seawater feed is the novel adsorption cooling and desalination technology, which is thermally driven due to the regeneration process which can be achieved with waste heat.

As with absorption refrigeration, adsorption cooling and desalination takes advantage of the low boiling point of a refrigerant to remove heat from a secondary fluid to generate the cooling effect. The main difference is that the refrigerant vapour is then adsorbed by a porous solid rather than absorbed by a solution. Thermal energy is then used to regenerate the solid material, typically silica gel or metal–organic frameworks [158], to recover the refrigerant vapour through the desorption process. The adsorption refrigeration system fulfils the function of water desalination if seawater is used as the refrigerant: water is separated from the salt during the consecutive adsorption and desorption processes. However, in this configuration the cooling effect is

Table 9
Performance and temperature levels of on-board integrated absorption refrigeration systems studies.

Pair [-]	COP [-]	GeneratorTemperature [°C]	CondenserTemperature [°C]	EvaporatorTemperature [°C]	AbsorberTemperature [°C]	StudyTypology	Ref [-]
NH_3/H_2O	0.60–0.70	90 to 120	20 to 40	20 to 40	25	Theoretical	[152]
NH_3/H_2O	0.40–0.60	80 to 110	20 to 30	−5 to 0	–	Theoretical	[153]
NH_3/H_2O	0.45–0.55	–	25 to 36	−30 to 0	–	Theoretical	[154]
H_2O/LiBr	0.70–0.90	65 to 90	30	–	30	Theoretical	[33]
NH_3/H_2O	0.50–0.70	80 to 110	20 to 40	−5	25	Theoretical	[33]
H_2O/LiBr	0.61–0.64	98 to 99	–	–	–	Theoretical	[155]

Table 10
Absorption refrigeration costing elements, data gathered from [156].

Design	Heat Source	Cooling Capacity (kW)	$C_{s,Q}$(€/kW)	O&M Costs (cts/kW/h)
Single Stage	Hot Water	175	1945	0.195
		1540	746	0.065
	LP Steam	4620	584	0.032
Two Stage	HP Steam	1155	973	0.097
		4620	713	0.032
	Exhaust	1155	1070	0.097
	Fired	3500	648	0.032

limited to chilling temperatures between 0 °C and 5 °C due to the boiling point of seawater at low partial pressure.

A schematic representation of a two-bed adsorption refrigeration system with desalination function [58] is shown in Fig. 19. Adsorption-refrigeration devices can either fulfil purely a refrigeration effect at sub-zero temperatures or can provide a hybrid function of chilling and desalinating seawater. As with most WHR technologies, the cycle efficiency can be improved through design. Typically, multiple adsorption bed systems are used. In the literature can be found the investigations of three [159] and four bed systems [160], with typical maximum cooling power around 100 kW. Due to the low maturity of the technology, costing data is sparse. Sorption refrigeration and desalination is a novel technology. Techno-economic performance data is likely to be similar to adsorption refrigeration without the desalination function, with a likely increase in investment cost from the increased system complexity, with salt precipitation inducing corrosion, but an increased return from the desalinated water reducing the load onto traditional desalination technologies that might already be on-board. Table 11 shows some tentative costing element derived in this way.

Palomba et al. [14] proposed a hybrid sorption cooling and desalination system combined with a conventional vapour-compression refrigeration cycle for on-board integration on a fishing vessel; two cooling temperatures are needed to meet refrigeration needs, chilling between −5°C and 0 °C, and refrigeration between −40 °C and −21 °C. The former temperature range is reached with the sorption component, while the latter temperature range by the vapour compression component of the system. The system is shown schematically in Fig. 20. The device reaches COP of 0.06 and specific cooling power 75 to 35 kW/kg, depending on seawater temperature which acts as the heat sink in the condensation process. The authors also discuss various configurations, cycle modifications and performance in the indicated reference. Lu and Wang [161] also investigated an adsorption refrigerator for on-board applications, which uses engine exhaust gas as primary heat source. System reached COP of 0.29 with seawater temperature of 28 °C.

Adsorption cooling and desalination is currently in the research and development phase. The primary areas of focus include enhancing efficiency by reducing energy consumption and optimising the integration of these devices into maritime environments. Specific areas of interest

Table 11
Cooling capacity and specific cost of various adsorption chillers.

Model	P_{cool} [kW]	$C_{s,Q}$[€/kW]	Study Typology	Ref
InvenSor LTC30 e plus	10 – 35	1,327	Commercial	[162]
SorTech eCoo 2.0 Silica Gel IP20	16	1,188	Commercial	[163]
Unnamed Silica gel / water adsorber	8	1,331	Prototype	[164]

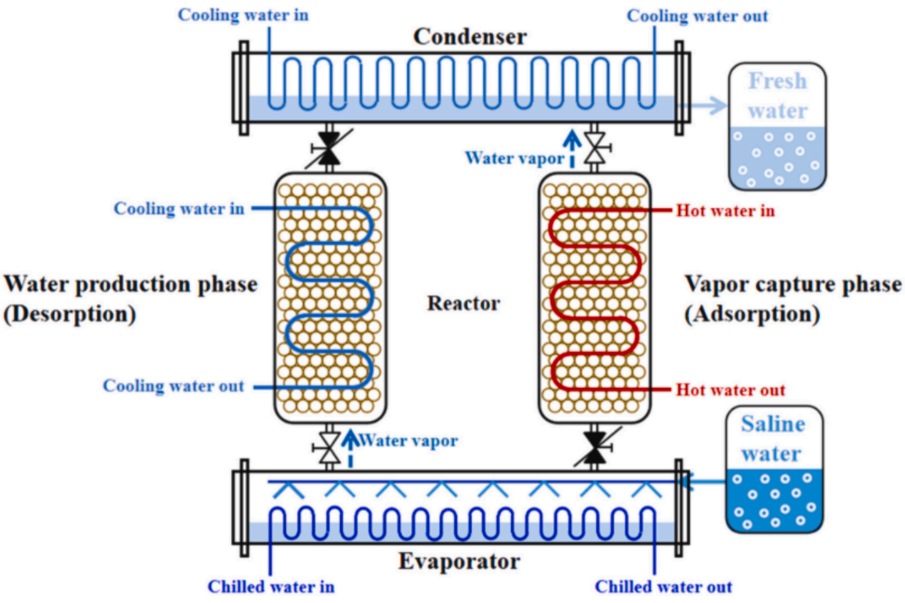

Fig. 19. Schematic representation of two-bed adsorption refrigeration system [58].

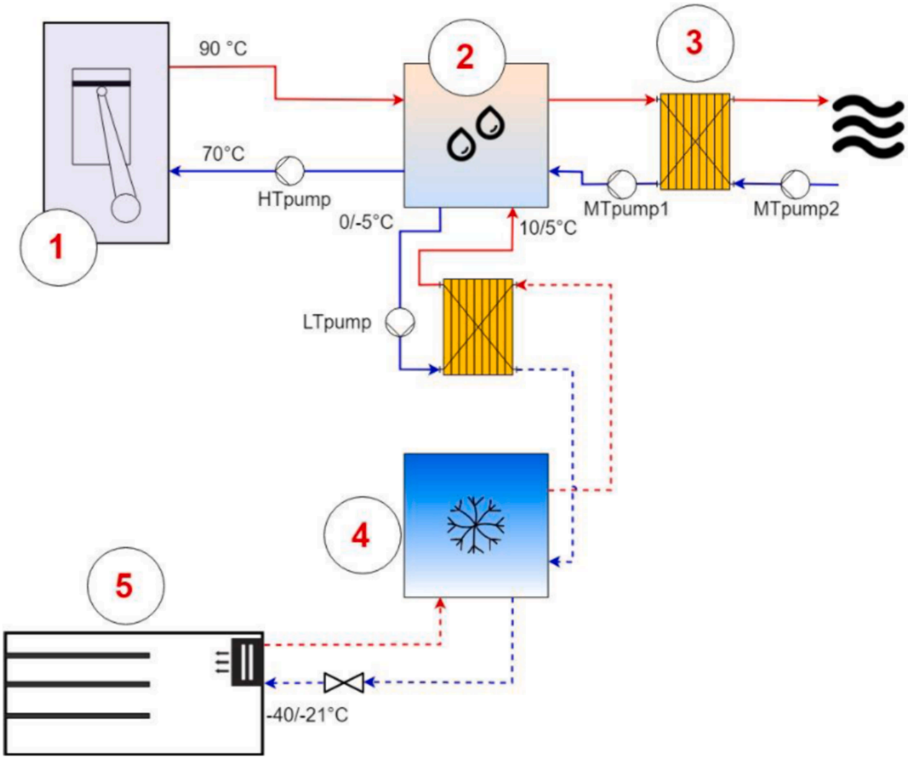

Fig. 20. Cascade sorption cooling and desalination and vapour compression cycle for integration in on-board energy system of a fishing vessel [14].

typically involve enhancing adsorbent materials, improving system performance under varying operational conditions, addressing scalability and reliability issues, and exploring innovative integration strategies to minimise environmental impact and operational costs [157].

5.3.3. *Hybrid refrigeration*

Hybrid refrigeration is a technology that combines various types of heat-driven refrigeration cycles.

It has attracted attention in the context of WHR and particularly in recovery of heat from diesel engines to power cooling systems. Although not universally accepted, it should be seen as a immature technology

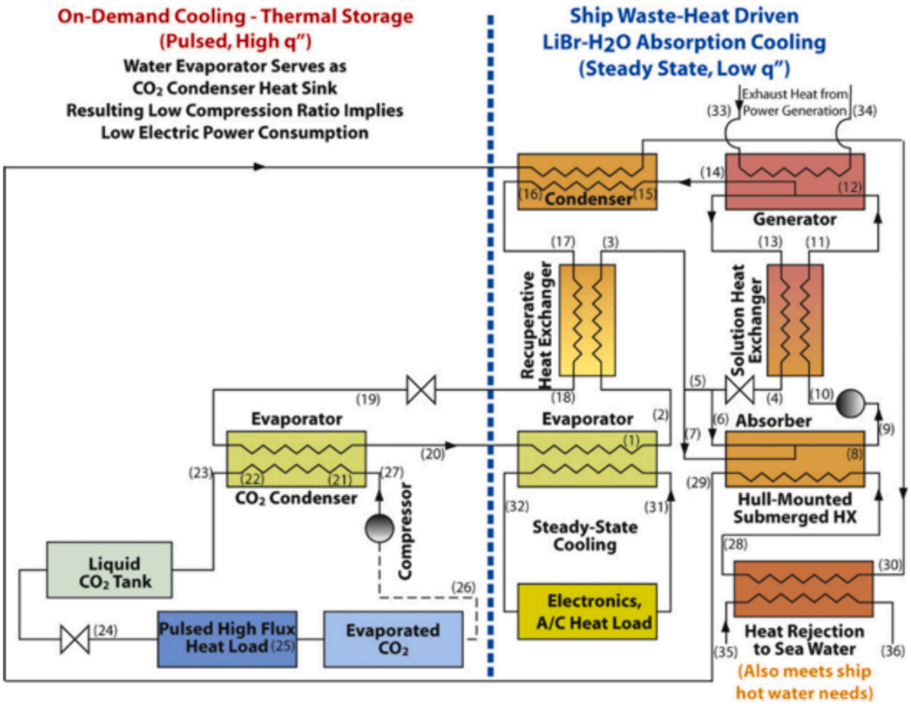

Fig. 21. Cascade hybrid refrigeration system, consisting of a conventional CO_2 compression cycle coupled to a single-stage LiBr-H_2O absorption refrigeration cycle [166].

given that even recent reports on marine refrigeration technology dismiss hybrid refrigeration [135], suggesting that this technology has simply not yet been installed on ships [165]. However, the technical potential of this technology has been demonstrated, and considering the increased pressure to decarbonise shipping, relating to the environmental impact of some refrigerants and the high electrical consumption of conventional refrigeration systems, hybrid refrigeration can indeed be considered a novel, emerging heat-to-cooling technology for marine WHR and is thus reviewed in the present work. Among the most studied configuration is the cascaded vapour compression and absorption hybrid refrigeration device; other cycles have been suggested, but not in the context of marine applications. This section therefore focuses specifically on cascaded vapour compression and absorption hybrid refrigeration devices.

Garimella et al. [166] investigated a cascade hybrid refrigeration system for on-board applications, a single-stage LiBr-H_2O absorption refrigeration cycle coupled to a subcritical CO_2 vapour-compression cycle. The system is shown schematically in Fig. 21. The heat rejected during CO_2 condensation in the vapour compression part of the cycle is partially used to evaporate the working solution in the absorption refrigeration section via an intermediate heat transfer loop. In the feasibility study it was estimated that the hybrid refrigeration system could deliver two cooling streams: a low temperature refrigerant stream exiting the evaporator at -40 °C aimed at cooling shipboard electronics which according to the authors require heat dissipation at a rate approximately 1 kW/cm^2, and a low-to-medium temperature refrigerant at 5 °C that could be used for air conditioning. Compared to a conventional vapour compression device, the proposed hybrid refrigeration system theoretically delivered the same cooling load with a 31 % reduced electrical consumption.

A hybrid refrigeration system consisting of a cascaded absorption and vapour compression refrigeration systems was also investigated for maritime applications by Cao et al. [167]. Their motivation was to provide an alternative to conventional vapour-driven refrigeration system on reefer container vessels which are essentially refrigerated cargo ships and consequently command a significant electrical consumption. They argue that since the containers on reefers have vapour compression cooling system attached to the sides, complete replacement by heat-driven systems is virtually impossible, but retrofitting a hybrid device that makes use of the existing vapour compression system is an attractive solution. The schematic representation of the hybrid system and the interfaces with the on-board energy system is shown in Fig. 22. The exhaust gases of the engine are exploited to heat a flow of hot water, which drives an absorption refrigeration cycle supplied by seawater and yields chilled water. Part of the chilled water flow is utilised to cools air for providing air conditioning on the vessel. The remaining part of the chilled water flow serves as a heat sink for the condensers of the vapour compression cycle through a dedicated heat exchanger using water and air. A conventional vapour compression system would use air for condensation at higher temperatures than the air cooled down by chilled water generated by the absorption cycle. This entails a lower value of the condensation pressure and, thus, a lower electrical consumption. It was found that the increased weight of the hybrid system over the conventional vapour compression system had negligible effect, mostly offset by lower fuel requirements. Indeed, the ship total weight decreased by 11 % with the more complex hybrid device on-board as 4 tons less fuel and fewer diesel auxiliary generators were needed.

Table 12 summarises the key performance indicators for the hybrid refrigeration systems discussed in the two previous paragraphs. COP and temperature are provided for the vapour compression cooling section (VCC), and the absorption chilling section (ABC) and the complete system (total). These COPs were calculated by the original authors of the studies and consider waste heat as 'free'. Indeed, only the electrical consumption of the cycles was considered for energy inputs. As a

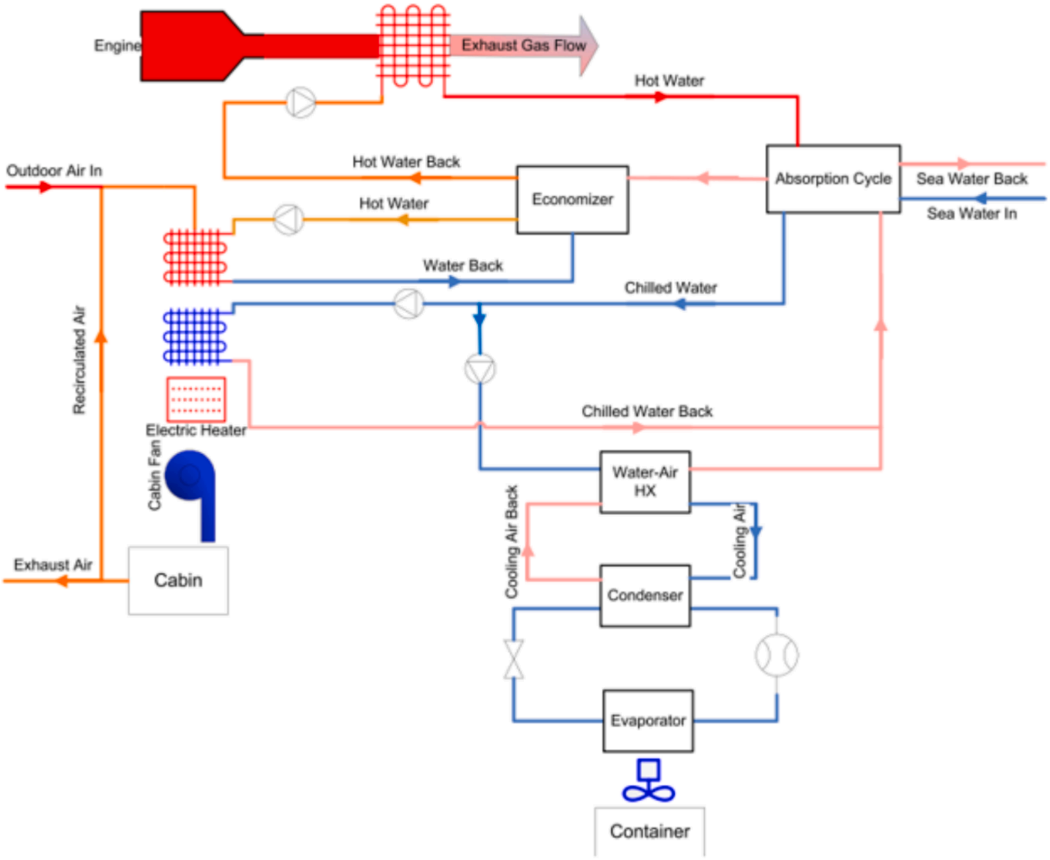

Fig. 22. Cascade hybrid refrigeration system integrated to a on-board energy system [167].

Table 12
Cooling capacity and specific cost of hybrid refrigeration systems.

	P_{cool}	Temp	COP	$C_{s,Q}$	Ref
	[kW]	[°C]	–	[€/kW]	–
VCC	82,000.00	5	2.17	–	[166]
ABC	51,000.00	−40	0.78		
Total	133,000.00	–	5.69		
VCC	108.41	7	1.92	4334	[167]
ABC	35.37	−20	0.59		
Total	143.78	–	2.00		

relatively immature technology system cost data is sparse, however Cao et al. provide a specific cost value for their system which is reported in the table.

Hybrid refrigeration is presently undergoing research and development. Primary areas of investigation involve optimising system configurations to maximise energy efficiency, exploring innovative hybrid system designs that combine multiple refrigeration and desalination technologies, and evaluating the environmental and economic advantages of such integrated systems in contrast to conventional standalone units [165].

5.4. Heat-to-mechanical

5.4.1. Isobaric expansion engines

Isobaric expansion engines (IEEs) convert heat to mechanical work through a non-polytropic near isobaric gas expansion process inside a cylinder [66]. Various designs, namely the Savery, Newcomen and Watt pumps [168,169], the Worthington direct-acting steam engine [170] and the Bush thermocompressor [171] were proposed. This technology has recently attracted the attention of technology researchers due to the potential for converting heat at very low temperatures around 40 °C and with small temperature differences of about 30 °C [172,173].

Fig. 23 shows schematically a Worthington engine, which is the most mature design of the IEE technology when applied to on-board WHR in the case where heat from exhaust gases is used to generate steam to power the IEE. Pistons **3** and **4** inside the steam cylinder **1** and pumping cylinder **2** are rigidly connected by a connecting rod **5**. Items **6** and **7** are the steam inlet and outlet valves respectively, whilst items **8** and **9** are the liquid inlet and liquid outlet valves. At the beginning the cycle, steam inlet valve **7** is opened, letting steam enter cylinder **1**, pushing piston **3** outwards and piston **4** inwards. During the entire stroke, steam enters at constant pressure with the inlet valve kept open, resulting in the so-called isobaric expansion. Cylinder **4** pumps the liquid out of cylinder **2** through the self-acting outlet valve **8**. When pistons **3** and **4** have fully displaced to the right-hand side, steam inlet valve is closed, while liquid enters pumping cylinder **2** through the liquid inlet valve **9**, pushing piston **4** outwards. Piston **3** displaces steam out of cylinder **1** through steam outlet valve **6** that is now opened until both pistons have fully moved to the left, thus completing the pumping cycle.

Overall efficiency can be improved at the expense of simplicity with recuperative heat exchangers and thermal barrier membrane-based pistons. Different working fluids as water or steam can be used, to generate work from heat at a variety of temperatures, a particularly useful feature given the multiple waste heat stream available in on-board energy systems. More detailed descriptions of IEEs with alternative layouts [173]. For common types of IEEs (Worthington and Bush), efficiency is around 5 % for net work output below 1 kW as stated in Table 13.

IEE technology in its modern iteration is still at a developmental stage, such that almost no documented examples of integration on real ships are available. Most of the research has been carried out in the past decade by researchers at Encontech BV [175], and consists of proof of concepts and laboratory apparatus. However, potential use of the mechanical work output of IEEs can be envisioned in on-board energy systems. Direct acting steam pumps were and are still designed either as boiler feed pumps or as ship emergency pumps [66]. Isobaric expansion engines can replace conventional electrically powered compressors [176], such as in compressed air or vapour compression refrigeration devices.

Waste heat can be directly converted by isobaric expansion engines into linear mechanical power to operate the engine fuel injection system or to directly power other volumetric pumps. This utilises the linear motion of the IEE piston, avoiding the need for intermediary conversion to electricity. Alternatively, the linear motion of the IEE piston can be transformed into electricity through an electric generator, with the electricity then utilised. This dual energy conversion approach is increasingly explored in flagship projects aimed at decarbonising ships and vessels [177]. An attractive aspect is the potentially low temperature heat needed by the system to yield useful work. An IEE could be located downstream of another WHR technology on-board, such as a turbine cycle exploiting heat from the exhaust gas stream from 350 °C to 200 °C for steam production; the IEE could then harvest energy from the already depleted waste heat stream from 200 °C down to the acid dew point of the exhaust gases around 140 °C-160 °C. In summary, the generated work can be used to power compressors and pumps [66], water desalination systems [178] or it can be converted into electrical power by connecting the device to a hydraulic circuit and a generator [66].

Currently undergoing research and development, the main priority lies in fundamental research to engineer systems finely tuned to this specific application. In particular, enhancing the performance is needed

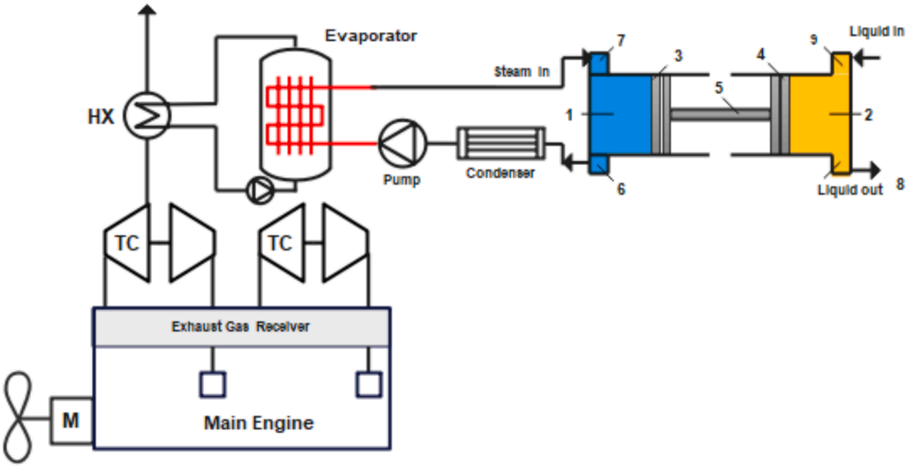

Fig. 23. Schematic representation of the basic working principle of Worthington steam pump in the context of marine WHR.

Table 13
Performance characteristics of IEEs compared to thermal power pump (TPP). Data originally gathered in [163].

	Cylinder Volume [L]	ΔP [bar]	Cycle period [s]	P_{mec} [W]	P_v [W/L]	η [%]	Ref
TPP system	1.8	2	200	1	0.6	0.5	[174]
IEE-Bush	0.02	15	2.5	20	1200	6.4	
IEE-Worthington	1	23	4	500	500	5.4	

to meet the specific demands and challenges of maritime applications. This encompasses optimising the design and operation of isobaric expansion engines to improve fuel efficiency, diminish emissions, and boost power output, all while ensuring reliability and durability in the demanding marine environment. Furthermore, research may delve into investigating alternative fuels and energy sources that align with isobaric expansion engines to advance sustainability and environmental responsibility within the shipping industry [66,177].

5.5. Thermal energy storage

Thermal energy storage (TES) is a technology used to store and release heat, helping solve the potential temporal mismatch between waste heat availability and on-board energy demands and acting as a supporting technology in the context of marine WHR. Fig. 24 schematically represents the TES interconnected between Diesel engine and the demand side. Storage of thermal energy is carried out through three methods [179]: (a) sensible thermal energy storage (STES), where heat is stored or released by increasing or decreasing the temperature of a solid or liquid [180]. STES materials include water, rocks, sand, molten salts, and metallic materials. (b) Latent heat thermal energy storage (LTES), where heat is stored in a phase change material (PCM) at nearly constant temperature during phase transition between solid and liquid [181]. (c) Thermochemical energy storage (TCS), where heat is stored or released as the reaction enthalpy of a reversible exothermic or endothermic reaction [182]. Typical thermochemical reactions for TCS include water sorption onto zeolite or other sorbents, hydration of inorganic salts, carbonation, oxidation–reduction reactions, among others.

The typical STES energy storage density, which is in the interval between 30 and 80 kWh/m^3 [183], is relatively low, hence potentially precluding its use for on-board WHR, where compactness of WHR technology is paramount. For such reason LTES or TCS appears to have greater appealing due to higher energy storage density, as highlighted by the growing interest and studies about mobile TES in terrestrial industrial WHR [184,185], a field that presents similar challenges to on-board WHR as high temperature waste heat and need for high storage density. Some effort has been made in the scientific literature to investigate PCMs for applications in relation to terrestrial vehicles diesel engine WHR, a summary of which is shown in Table 14. PCMs with solid/solid and solid/liquid phase transitions can be divided into organic paraffins, organic non-paraffins, inorganics and eutectics. The primary drawback of LTES is the low thermal conductivity of PCMs, generally below 1 W/m/K [186], which limits the charge and discharge power. TCS is less developed than LTES, and as such specific material studies for terrestrial or marine Diesel engines are largely absent. Table 15 provides still a selection of TCS reactions from both 'reaction' and 'sorption' categories that are both typical of TCS and display potential for on-board WHR. Currently, the main limitations of TCS are the low technological maturity, high system complexity, and a lack of successful implementations into real energy systems.

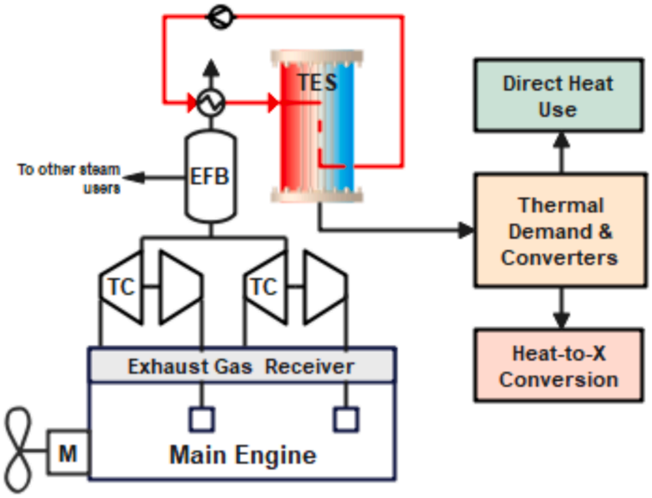

Fig. 24. Schematic representation of the integration of TES to a on-board energy system.

A major barrier to TES integration on-board is that currently most commercial TES are STES devices. Some are compact STES which can receive excess heat with high temperature fluctuation. Energy Nest designed a modular STES, the Thermal Battery which charges with temperatures up to 400 °C. It is a concrete storage with metallic components for structural rigidity and enhanced heat transfer [202]. Eco-Tech Ceram designed an STES system, EcoStock which charges with temperatures up to 1,000 °C using ceramic-metallic materials [203]. Lumenion [204] instead proposed, designed and developed a STES solution based on steel. Nonetheless, the above mentioned STES have been developed for industrial applications, solar-thermal applications, or power-to-heat applications. Their suitability and applicability for on-board WHR remains uncertain and unproven. In such regard, particular attention should be given to footprint and weight of these STES, since both space and weight are at high premium on any ship.

Further performance and characteristics of TES systems, particularly for LTES, are shown in Table 16. The energy storage density shown in this table pertains to system-scale energy storage density based on the complete TES volume, differently from the material-scale energy storage densities shown in previous tables when dealing with the different types of TES materials. The reported energy storage density at system-scale is lower than the material-scale storage density due to essential auxiliary components and parts of the TES as piping, heat exchangers and thermal insulation, which however do not contribute to the energy storage capacity.

Table 14
PCMs and their heat storage properties for internal combustion engine WHR, list originally compiled in [187].

Compound	Type	T_{melt} [°C]	E_d [kWh/m^3]	Ref
$Na_2SO_4{\cdot}10H_2O$	Inorganic	32.4	104.78	[188]
$Na_2HPO_4{\cdot}12H_2O$	Inorganic	36	112.04	[189]
Lauric Acid	Organic	41–44.2	59.19	[190]
Stearic Acid	Organic	55.1	37.69	[191]
$NaOH{\cdot}H_2O$	Inorganic	58		[192]
Paraffin wax	Organic	58–60	46.96	[193]
Climsel C70	Inorganic	70	68.00	[193]
D-Sorbitol	Organic	89–95	78.37	[194]
Xylitol	Organic	92–94	106.80	[195]
Na	Inorganic	91	29.19	[196]
Erythritol	Organic	117.6	139.70	[197]
73 %NaOH/23 %$NaNO_3$	Eutectic	237	174.30	[198]
59 %LiCl/41 %KCl	Eutectic	352.7	131.34	[199]
$NaNO_3$	Inorganic	307	107.83	[200]

Table 15
TCMs and their heat storage properties, list originally compiled in [201].

Compound	Type	$T_{reaction}$ [°C]	E_d [kWh/m^3]
Zeolites	Sorption	25–230	136–200
Salt Hydrates	Sorption	24–214	361–867
Composites	Sorption	30–250	166–308
Ammonia Based	Reaction	350–750	< 830
Metal Based	Reaction	300–1400	8–3–2050
Carbonates	Reaction	500–1730	300–889

Table 16
Techno-economic performance of various TES devices, data originally synthesised in [61].

Type	Material	E_d [kWh/m^3]	η	Volume [m^3]	SCC [€/kWh]	Ref
Shell and tube LTES	$NaNO_3$	43	–	700	–	[205]
Shell and tube LTES	KNO_3 / $NaNO_3$	39	–	58	–	[206]
Packed bed LTES	Li_2CO_3/ K_2CO_3/ Na_2CO_3	66	80 %	2	–	[207]
Packed bed LTES	$NaNO_3$	86	–	1	–	[208]
Shell and tube LTES	Al-Si (88–12)	29	–	14	–	[209]
Shell and tube LTES	Al-Si (88–12)	35	–	13	–	[210]
Packed bed LTES	Li_2CO_3/ K_2CO_3/ Na_2CO_3	115	61 %	83,333	–	[211]
Packed bed LTES	KNO_3	190	–	50,000	–	[212]
Packed bed LTES	Al-Si (75–25)	83	39 %	0.4	–	[213]
Shell and tube LTES	KNO_3 / $NaNO_3$	–	70 %	–	–	[214]
Shell and tube LTES	Sodium Nitrate	–	–	77,161	65	[215]
Shell and tube LTES	Chloride + Carbonate Salts	–	–	–	18	[216]
Shell and tube LTES	KOH	–	–	83,333	19	[217]
Shell and tube LTES	Sodium acetate trihydrate	68	90 %	7	–	[218]
Packed bed LTES	D-mannitol	101	–	14,806	–	[211]
Tube in tank LTES	Paraffin RT82	–	–	6	260	[219]
Tube in tank LTES	Sodium acetate trihydrate	–	–	2,500	58	[220]
Tube in tank LTES	Erythritol	–	–	2,000	40	[221]
Tube in tank LTES	Erythritol	–	–	2,400	17	[222]

Differently from active technologies, TES devices do not yield mechanical or electrical work, or other effects such as cooling or desalination, but rather they allow to match in space and time the intermittent engine waste heat with on-board energy demands. Thus, they should be designed for the on-board energy system, to synergistically interact between waste heat streams and other WHR technologies. On-board waste heat being obtained through multiple different streams and with high variance in temperature levels, from 50 °C lubricating oil stream to 300 °C exhaust gas streams, sets a significant design challenge since most TES materials are only able to store heat within a relatively narrow temperature range.

An approach suggested in the literature is to design TES system with a cascade of TES materials tailored to operate at different temperatures so that a wide range of waste heat could be stored. Pandiyarajan et al. [223] describe a cascaded LTES system using different PCMs with a range of melting temperatures, in order to leverage the multiple on-board waste heat streams and found a potential 10 % to 1 % fuel energy recovery. Such TES designs for on-board applications, however, remain so far theoretical, and their effectiveness have not been fully demonstrated so far with highly dynamic waste heat temperature profiles which are illustrative of real ship operation [224]. Thus, existing designs for marine TES tend to target a specific location of the on-board energy device to couple specific waste heat streams within a narrow temperature range with another WHR technology or on-board heat demand point.

For example, Baldi et al. [47] analysed the feasibility of a 1,000 m^3 thermal oil STES, which reduced fuel consumption in auxiliary boilers by 80 %. Here, TES is envisioned synergistically with other WHR technologies to compensate the intermittence of engine waste heat [225]. Frazzica et al. [49] designed a hybrid sensible-latent TES device specifically designed for the provision of domestic hot water on ships, using heat from the jacket cooling water. The device is pictured in Fig. 25. They used phase change material S58 designed by PCM products with melting point of 58 °C. The device is constituted of a bundle of 20 polypropylene tubes containing the macro-encapsulated PCM with a volume of 40 dm^3, all within a cylindrical tank with a volume of 100 dm^3 made of stainless steel. The system can deliver hot water between 65 °C and 85 °C with a discharge power between 15 kW and 20 kW.

The process leading to the utilisation of TES devices on board vessels is presently progressing through the research and development phases. The key hurdles to overcome include designing systems tailored to this application, integrating them with existing ship systems and other technologies, maximising energy storage density, minimising physical footprint costs, and optimising the duration of thermal charge and discharge cycles [49,226].

6. Summary KPIs and challenges

The following Table 17 summarises the reviewed technologies and provides cross-comparative summary of their techno-economic KPIs. Considering the archetypal marine energy system with up to 80 MW engine capacity, the combined capacity and energy recovery of the analysed WHR technologies can improve marine energy efficiency and CO_2 emissions. In terms of deployment, technologies are generally either (a) fully deployed in the marine WHR context (turbo-compounding) with favourable KPIs such as wide range of capacities and low costs, (b) deployed in traditional WHR contexts but have not been suitably adapted yet to the marine environment as ORC absorption refrigeration or (c) at a research and development stage and thus manufacturers have not attempted deployment. All the technologies require integration with existing ship systems, reduction of capital expenditure and operational costs, and adherence to regulations.

For most system heat recovery cannot be expected to be higher than 40 %, except for TES devices which would ultimately be used as buffer solutions to discharge heat towards one of these technologies, and refrigeration systems which have the potential for high COP and other

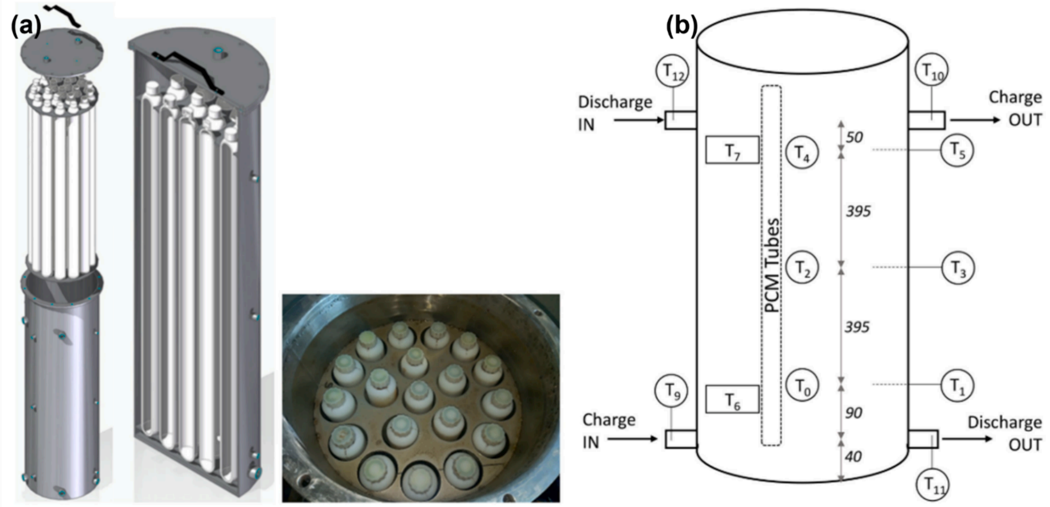

Fig. 25. Hybrid STES and LTES for on-board waste heat storage, targeted towards hot water production (a) detailed exploded tri-dimensional view and (b) schematic representation with sensors and flow direction [49].

Table 17
Summary and cross-comparison of on-board WHR technologies and their KPIs.

Technology	Capacity	Performance	Cost	Deployment
Turbocompounding	500–20,000 + kW	η = 3–20 %	100–3,500 €/kW	Deployed
Organic Rankine Cycle	10–10,000 kW	η = 5–25 %	1,000–100,000 €/kW	Deployed in traditional WHR
Kalina Cycles	20–100,000 kW	η = 7.5–35 %	1,000–3,000 €/kW	Lack of experimental devices
Thermo-Electric Generation	1–80 W	η = 1–20 %	1,000–15,000 €/kW	High cost for deployment in rugged exhaust gas lines
Absorption Refrigeration	150–5,000 kW	COP = 0.1–0.6	500–2,000 €/kW	Deployed in traditional WHR
Adsorption Desalination and Cooling	1–50 kW	COP = 0.2–0.8	1,000–1,500 €/kW	At R&D stage
Hybrid Refrigeration	35 – 80,000 kW	COP = 0.5 – 2.5	~5,000 €/kW	At R&D stage
Thermal Energy Storage	50–200 kWh/m3	η = 50–100 %	1–100 €/kWh	Marine WHR devices at R&D stage
Isobaric Expansion Engine	1–1,000 kW	η = 1–14 %	500–2,500 €/kW	At R&D stage

added value (desalination) but are still at an immature technological readiness level for marine WHR.

A major challenge of WHR technologies lies in their practical applicability on board vessels. The available space is limited, requiring relevant modifications to the existing piping layout to integrate the equipment. Moreover, there are potential disruptions to existing infrastructure, energy systems, and established service and maintenance practices. Another noteworthy challenge is the relatively high CAPEX associated with certain technologies, such as ORCs, Kalina cycles, TEGs, and adsorption chillers. This is compounded by the lack of detailed techno-economic studies that consider realistic waste heat profiles and energy demands, which could convincingly demonstrate their economic feasibility. This lack of studies makes ship owners and other stakeholders hesitant to install WHR technologies as they seek very high returns of investment and low payback periods. This keeps their interest focused on traditional energy efficiency solutions to reduce the risk. The situation is aggravated by the complexity of the optimal sizing and thermodynamic optimisation of novel solutions which require technical expertise usually lacking in industry. These challenges complicate and slow down the adaptation of WHR technologies on-board existing vessels.

Further aspects of the possible future investigation of technologies for waste heat exploitation are the analysis and comparison of the techno-economic parameters and life cycle environmental impact of the various solutions. To these is added the evaluation of the suitability and prioritisation of the technologies for ranking them for different vessel types based on their waste heat and energy demand characteristics and size.

7. Conclusions

This article reviewed the main existing and emergent and novel waste heat recovery technologies for ships. The aim was to provide an organised and updated structure for the classification of emerging and current but highly relevant waste heat recovery solutions for on-board energy systems. The article provides a valuable tool that contributes to the urgently needed decarbonisation of the shipping industry. It emerges from the review that waste heat recovery technologies selected and sized based on the architecture of the existing onboard energy device of interest, available waste heat and energy demands. The reviewed set of technologies display different operational temperatures, which suggests that a cascade of waste heat recovery solutions, where waste heat is systematically converted and downgraded before driving the next downstream technology, could be a viable approach if available space on-board permits the installation. The literature approach to analysing WHR technologies for on-board applications primarily relies on the first law definition of efficiency. However, adopting a systematic approach grounded in the second law definition of efficiency and exergy could be pursued to ensure the accurate design of geometric and operating conditions.

Regarding specific technologies, turbine-based power cycles dominate the space of electrical power generation. Organic Rankine cycles and turbocompounding, the latter being already found onboard, show the highest technological readiness level and yield. Other technologies could theoretically contribute, such as thermoelectric generation or Kalina cycles, but lack in maturity or techno-economic potential to be seriously considered in the current state-of-the-art. Thermal energy storage is a passive technology that should be designed to operate synergistically with other waste heat recovery technologies. This technology has not been strongly considered so far by the on-board waste heat recovery literature, yet due to the highly intermittent nature of waste heat and energy demand patterns, it has high potential to directly improve the performance of onboard energy system with relatively low physical imprint on the energy device. The temperature level during the discharge combined with reasonable technological readiness level make latent thermal energy a promising solution to fully explore. Due to the synergistic nature of thermal energy storage and apparent lack of studies, integration of thermal energy storage with one or more other solutions could be a pathway to highly efficient on-board energy systems, which should be investigated theoretically and experimentally.

Alternative on-board cooling and desalination technologies are emerging as well. This is the case of thermally driven sorption-based systems which show the attractive feature to be capable to provide cooling and as fresh water as a valuable by-product of the underpinning sorption and desorption processes. Nonetheless, the amount of cold and of fresh water transformed per unit of input energy remains relatively small compared to traditional vapour compression systems or flash desalination systems. The relevant efforts toward sustainability, also for what concern displacement of traditional refrigerants, might accelerate the rate of development and adoption of sorption-based system on-board of vessels. Further, synergic opportunities for hybridisation like between vapour compression systems and sorption ones, should be explored.

The technologies presented in this review span a temperature range between 50 °C and 350 °C, a variety of technological readiness levels from laboratory experimental prototypes to relatively established technologies in terrestrial applications that require more demonstration in on-board energy systems, and power capacities from a few W to MW-scale systems. This review can directly be used by technology and device engineering researchers as a knowledge resource to further the investigation of waste heat recovery in on-board energy systems, to ultimately progress the end goal of fully decarbonising the maritime transport sector.

CRediT authorship contribution statement

Robin Fisher: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lorenzo Ciappi:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Pouriya Niknam:** Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Konstantinos Braimakis:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Data curation. **Sotirios Karellas:** Writing – review & editing, Validation, Resources, Project administration, Funding acquisition, Conceptualization. **Andrea Frazzica:** Writing – review & editing, Validation, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Adriano Sciacovelli:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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