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Innovative waste heat valorisation technologies for zero-carbon ships - a review

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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 large vessel emissions. Waste heat recovery is an effective way to improve ship energy efficiency, lower the temperature and amount of waste heat rejection to the environment, and therefore curb green-house gas emissions. In this article, existing and developmental on-board waste heat recovery technologies for maritime applications are reviewed. Emphasis is placed on the integration and performance of these technologies within the broader on-board energy system. Performance indicators are drawn from existing systems, experimental prototypes, and simulations, to quantitatively compare the different technologies in terms of power capacity, efficiency / coefficient of performance, heat source temperatures and specific cost of installation.

Keywords:

Energy; ECOS Conference; Waste heat recovery; Sustainability.

1. Introduction

It is estimated that the totality of vessels above 100 tons are responsible for approximately 3% of global greenhouse gas emissions [1]. Furthermore, shipping for international trade is expected to grow further in the immediate future [2]. Consequently, the International Maritime Organisation has set the objective of halving naval-related emissions by 2050 [3]. Engine waste heat recovery (WHR) is a possible pathway to decarbonising marine shipping. In large-bore two-stroke diesel engines, which are the propulsion method of choice in 96% of ships above 100 tons [4], approximately 50% of the fuel input is lost as waste heat through exhaust gases, cooling fluids and radiation [5]. On this basis, developing on-board WHR is a viable strategy to improve ship energy efficiency and curb sector wide global greenhouse gas emissions.

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. [6]	Singh et al. [4]	Xu et al. [7]	Zhu et al. [8]	This review
Turbo-compound systems	x	x			x
Turbochargers	x	x			
Absorption Refrigeration	x		x		x
Adsorption Refrigeration	x		x		x
Thermoelectric Generation	x	x			x
Organic Rankine Cycle	x	x		x	x
Steam Rankine Cycle	x	x		x	x
Kalina Cycle		x		x	x
Thermal Energy Storage					x
Isobaric Expansion Engines					x

WHR has been demonstrated as viable by Baldi and Gabrielli [9] who showed that WHR systems with 2- to 5-year payback times, reducing fuel consumption by 4% to 16% respectively, are achievable. Marine WHR

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technologies have previously been reviewed by Shu et al. [6], and by Singh and Pedersen [4]. However, these reviews are not recent (2013 and 2016, respectively), and are discrepant on the classification and selection of WHR technologies. Shu reviews exclusively turbine based WHR technologies, including power cycles, Rankine cycle and various forms of Turbocharging (**Table 1**). Turbocharging always features in large vessels, and should arguably be classified as relevant to the engine technology and operation rather than part of the WHR system [10]. Furthermore, other WHR technologies exist, such as refrigeration systems, which are discussed in Singh's review, or thermal energy storage or isobaric expansion technology which are novel and have never been reviewed as marine WHR technologies. Some reviews have been published which focus on specific applications of engine WHR. Palomba et al. [11] evaluated the feasibility of applying WHR for powering on-board refrigeration and cooling systems on fishing vessels with some suggestions for system configurations and integration, while Xu et al. [7] specifically reviewed the available technologies for on-board refrigeration which were broadly categorised into absorption, adsorption and hybrid refrigeration system, with a partial focus on components. Zhu et al. [8] specifically reviewed marine engine WHR with bottoming power cycles, which consist of traditional Steam Rankine Cycles, Organic Rankine Cycles (ORC), and Kalina cycles. A summary of existing literature reviews focused on on-board engine WHR, and the discussed technologies is shown in **Table 1**.

1.1 Motivations & specific aims

Modern ships are evolving, and are being considered more and more as multi-energy systems, i.e. systems in which different types of energy (thermal, cooling, power, propulsion) and utility (clean water, steam) demands are designed to interact optimally with one another [12]. In view of this development and in the light of the existing literature landscape surrounding WHR technologies, the specific aims of this article are to provide a systematic, holistic, and up to date review of the current and developmental WHR technologies for marine applications and specifically the recovery of engine waste heat. Taken into account are the working principle, the possible integration to the marine energy system, and, when available, techno-economic performance measured in terms of efficiency / coefficient of performance, power capacity and specific cost.

2. State of the art of on-board WHR technologies

2.1 Waste heat recovery heat exchangers

A conventional on-board WHR method direct recovery from exhaust gases through a WHR heat exchanger, and directly provide for one of the on-board thermal energy demands. With a WHR heat exchanger system, exhaust gases flow in the hot side, and exchange heat with water or air flowing in the cold side. According to Baldi et al. [13] and Jouhara et al. [14], 5 such technologies can be highlighted for marine energy systems:

- **Economisers**: finned tube heat exchanger designed for low to medium temperature waste heat, aimed at heating boiler feedwater in view of steam generation in a separate piece of machinery.
- **Waste heat boilers**: medium to high temperature exhaust gases pass through the tubes of this heat exchanger, exchanging heat with water flowing on the cold side with the aim to generate steam.
- **Recuperators**: medium to high temperature exhaust gases pass the through the tubes of this HX hot side and exchange heat with the inlet air circulating in adjacent channels to provide for various on-board thermal energy demands.
- **Regenerators**: a type of heat exchanger with some thermal capacity to temporarily store thermal energy, with both hot and cold fluid asynchronously using the same channels. During a so-called hot phase, exhaust gases flow through the channels of the regenerator, storing heat into the heat exchanger's packing, generally a ceramic or refractory material. Cold fluid (air) is then circulated through the heat exchanger channels in a so-called cold phase to recover the stored heat.
- **Heat recovery steam generators**: a multiple-pressure heat exchanger system designed to produce high quality steam from high temperature exhaust gas waste heat. Such a system typically features three pressure levels: economiser, evaporator, and superheater.

2.2 Turbocompounding

Turbocompounding consists in utilising heat in the exhaust gas stream to power a turbine system and generate electricity. Turbocompounding is different from turbocharging, the latter being a method for recovering exhaust waste heat to compress the engine intake air. Advances in turbocharging technology have resulted in a surplus amount of energy in the exhaust gas stream compared to the requirements for intake air compression [4], encouraging further use of the exhaust gas waste heat potential through turbomachinery. In the best-case scenarios both turbochargers and a turbocompounding WHR system can be installed together to reach high WHR. According to MAN, one of the main manufacturers of turbocompounding systems [5] there are three options for turbocompounding, ordered here by increasing efficiency and complexity **PTG**: power turbine generator unit. A so-called power turbine directly converts exhaust gas energy to electricity, recovering a potential η =3-5% of fuel energy according to MAN. **STG**: steam turbine generator unit. Exhaust gas energy

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is used to generate steam in an exhaust gas fired boiler (EFB). The energy contained in the generated steam is then used to power a steam turbine. Such as system can achieve a potential 5-8% fuel energy recovery.

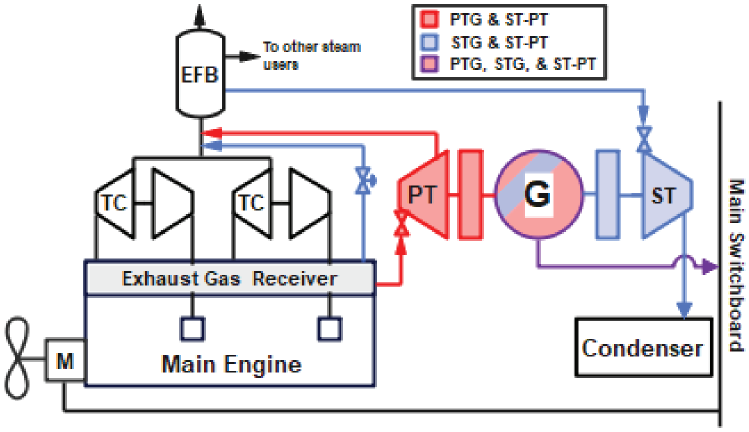

Figure 1 Schematic representation of turbocompounding WHR PTG system, STG system and combined ST-PT system.

ST-PT: combined steam and power turbine generator unit. Uses both preceding principles in a combined system with both turbines on the same shaft connected to the generator to potentially achieve 8-11% fuel recovery according to MAN, with a similar recovery ratio of approximately 10% for the Winterthur Gas & Diesel combined system [15]. These systems are shown schematically in **Figure 1**. In terms of maturity, turbocompounding is an established on-board WHR technology (technology readiness level~9) [13], favoured for its ease of installation and high retrofitting ability. To select the best turbocompounding system type, MAN recommend a PTG when the main engine power is below 15 MW, a STG for main engine powers between 15 MW and 25 MW, and the combined ST-PT for engine powers above 25 MW. **Table 2** shows typical specific installations costs and maintenance costs for the different types of turbocompounding systems. The data was synthesised by Olaniyi and Prause [16] from various turbocompounding WHR system manufacturers.

Table 2 Installation and maintenance costs for different types of turbocompounding WHR system, data originally collected in [16], costs actualized and converted from dollars to euros.

	Installation Costs [€/kW]	Maintenance Costs [€/year]
PTG	105	10,500
STG	320	21,000
PT-ST	420	32,000

2.3 Rankine cycles

Rankine cycles are a type of power cycle designed to convert thermal energy into useful mechanical power through an expander. The useful mechanical work is then converted to electricity via a generator. Thermal energy from the exhaust gases is used to evaporate a working fluid in the boiler (1 to 2). The working fluid vapour is expanded to the cycle's low pressure level in a turbine to produce useful work (2 to 3), then condensed (3 to 4), before being pumped to the cycle's higher pressure level (4 to 1) into the boiler, thus completing the cycle. The cycle presented in **Figure 2** shows a simple Rankine cycle layout using main engine exhaust gas as the heat source. Steam Rankine Cycles operate with water as the working fluid and thus require a high temperature heat source (T>200°C) [17], whereas Organic Rankine Cycles (ORC) use an organic working fluid with a lower boiling point to leverage lower temperature heat sources. Cycle performance is typically increased using modifications to the simple cycle such as regeneration, bleeding, and multiple loop cycles [18]. Regeneration involves a heat exchanger to extract residual thermal energy at the turbine outlet to pre-heat the working fluid between the pump and the boiler. Bleeding involves extracting part of the working fluid to preheat before boiler entry, and as a result a secondary lower pressure circuit which is expanded in a secondary turbine/expander. Multiple loop cycles involve two or more working fluids with different boiling points to leverage the multiple waste heat streams in marine energy systems. Most proposed systems for marine applications include one or several of these modifications. For example, Song et al. investigated the use of multiple waste heat streams as thermal energy source for a ~100 kW net power output ORC, with jacket cooling water for preheating and exhaust gas for the evaporation of the working fluid [19]. Lion et al. thermodynamically investigated a similar concept, except using hot scavenge air to preheat the working fluid and exhaust gas for evaporation [20]. Casisi et al. [21] modelled different ORC configurations for integration in marine energy systems: simple, regenerated and dual loop layouts. In these cases, the high temperature cooling water circuit was used to preheat the working fluid. Rankine cycles have high technology readiness level ~ 8, with market ready systems being commercially available. Conventional ORC manufacturers are Ormat, Turboden and GE [22], with systems mainly targeted towards biomass, combined heat and power (CHP), geothermal and industrial WHR.

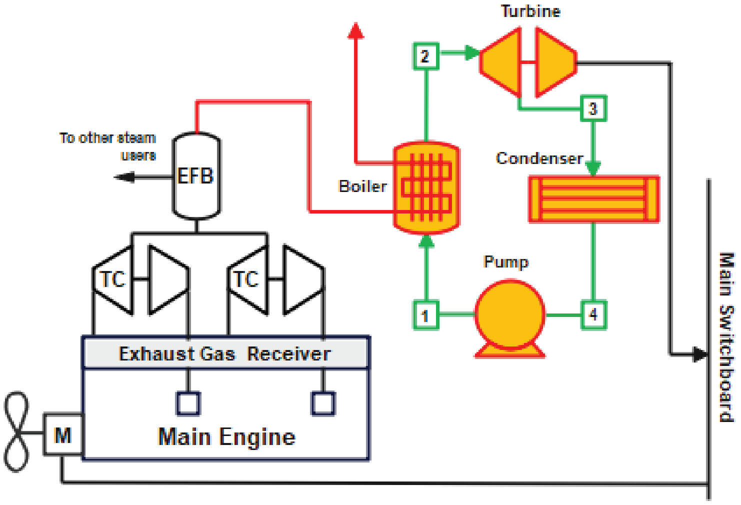

Figure 2 Schematic representation of a Rankine cycle WHR system using main engine exhaust gas as heat source.

Various manufacturers however offer ORC modules designed specifically for marine energy systems, such as Orcan-Energy's *Efficiency Pack* [23], Alfa Laval's *E-Power Pack* [24], or the Caltenix Mitsubishi partnership's *Hydrocurrent TM Organic Rankine Cycle Module 125EJW* [25]. The technical performance of some of these systems, both market ready and theoretical, is summarised in **Table 3**.

Table 3 Technical performance of marine ORCs (LT: low temperature, HT: high temperature)

Heat Source Temperature [°C]	Layout	Working Fluid(s)	Net Power Output [kW]	Efficiency	Ref
315	Basic	R123	625	16.38%	[26]
300 / 90	Dual Heat Sources	Cyclohexane	96	20.75%	[19]
300	Parallel ORCs	R245fa	101	10.20%	[19]
293.15	Regenerated	Benzene	396	22.00%	[27]
145	Regen.	Toluene	684	26.70%	[21]

Kalina cycles

Kalina cycles are a variation of the Rankine cycle, revolving around the evaporation of an ammonia-water mixture using the excess waste heat and operating an expander / generator train to generate electrical power [28]. The system was first introduced in 1983 as an alternative to ORCs, with higher efficiency and lower cost as the design objective. The crucial aspect of this cycle is that ammonia-water is a zeotropic mix, i.e., its boiling point changes with the respective mass fractions of the mix. 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. Various process units internally improve cycle performance including heat recuperation and solution enrichment/separation processes. Detailed description of the working principle can be found in the original publication by Kalina et al. [28]. While the diagram in Error! Reference source not found. shows a single waste heat source, exhaust gases, Kalina cycles are well suited to extract heat from multiple waste heat streams emanating from vessel diesel engine, such as preheating the zeotropic mixture with engine cooling circuits [29]. The performance and some main characteristics of various Kalina cycles for WHR are shown in **Table 4**. Data presented in this table were sourced mainly from theoretical literature studies, originally synthesised in [30]. The wide temperature range of heat sources from the WHR applications (98°C to 566°C), despite using the same working fluid (albeit in different mass fractions), and range of power outputs (21.7 kW to 8,600 kW), showcases the flexibility of the Kalina cycle in handling different waste heat sources. Efficiency of Kalina cycles tends to scale proportionally with plant size and is found in a similar range to Rankine cycles between 7.5% and 35%. The projected cost of Kalina cycles for various plant capacities is also shown in **Table 4**. The capital cost for Kalina cycle systems above 1 MW can range from 1,000 to 1,500 €/kW, while for smaller systems, below 1 MW, significantly higher capital costs in the 2,000 – 3,000 €/kW range should be expected.

Table 4 Characteristics and techno-economic performance of WHR Kalina cycles, data originally synthesized in [30]**.**

Heat Source	Temperature [°C]	Power [kW]	Efficiency [%]	Cost [€/kW]	Ref
Coal combustion flue gas	150	320	12.3	2,000 – 3,000	[31]
Engine exhaust gases & cooling	524 / 86.8	21.7	25.6	-	[29]
Engine exhaust gases	346	1,615	19.7	-	[32]
Gas turbine exhaust gases	566	3,137	28.6	-	[33]
Gas turbine exhaust gases	522	86,136	35.6	1,157	[34]
Geothermal	-	1,850	-	1,150	[35]
Cement Plant	-	6,000	-	1,500	[36]

Thermoelectric generation

Thermoelectric generation (TEG) is a technology designed to directly generate electricity from a heat input using the Seebeck effect: a temperature gradient between two semi-conducting materials produces a voltage gradient proportional to the temperature different. TEG is particularly valued for its ability to continuously deliver electricity, its compacity and ruggedness in challenging environments: the first major field of application of TEG was the space industry. Today TEG is investigated for industrial WHR, including in marine energy systems [37]. TEG is at a technological readiness level where various commercial devices are available, their techno-economic performance being shown in **Figure 3**. The main drawbacks of TEG are low heat-to-electricity conversion efficiencies (below 5%) and low volumetric power output.

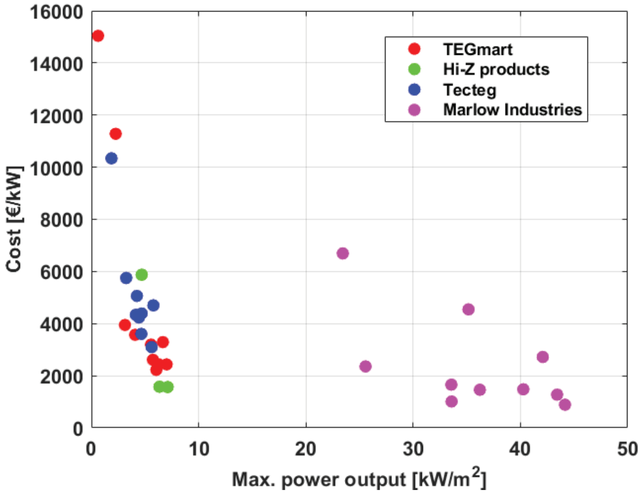

Figure 3 Commercial TEG modules techno-economic performance [38]–[41]**.**

Absorption refrigeration

The principle of absorption refrigeration revolves around leveraging the low boiling point of a refrigerant (typically ammonia). During this phase change the refrigerant will extract thermal energy from and cool down another fluid (typically water) yielding the intended refrigeration effect. A schematic representation of a simple single-stage absorption system is shown in the context of exhaust gas WHR in **Figure 4**. Cooling effect is produced in the evaporator where the ammonia evaporation process extracts thermal energy from a water flow which is sent to the vessel cooling load. Ammonia vapour then flows to the absorber to be absorbed to form a liquid solution, which is then pumped to a higher pressure towards the generator. The ammonia vapour is desorbed from the solution to a new vapour phase using water heated from main engine exhaust gases, and this vapour phase is then returned to liquid phase in the condenser, using sea water as cooling medium. The condensed ammonia phase then flows towards the evaporator, thus completing the cycle. Absorption refrigeration differs from conventional vapour compression systems for refrigeration, in that [42]:

- the vapour refrigerant is absorbed by a secondary substance to form a liquid solution before being pumped to a higher pressure. This process results in significantly less electrical work input compared to a vapour compression due to the much lower specific volume of liquid.

- the refrigerant is desorbed from the liquid solution using some thermal energy input before the condensation stage. Herein lies the main advantage of absorption refrigeration as it is a means to produce a cooling effect from a thermal energy source, thus making it highly relevant for marine energy systems with waste heat sources and potentially high cooling load.

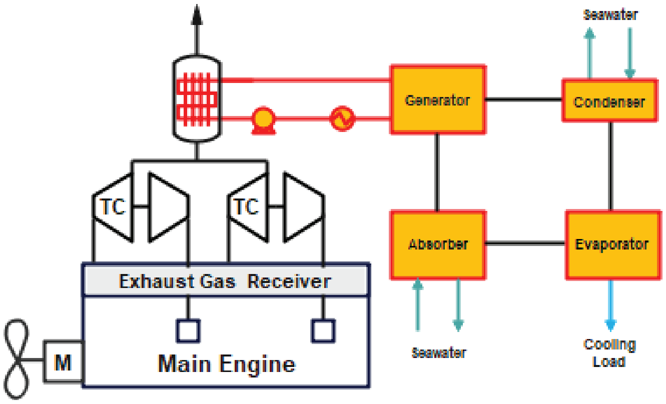

Figure 4 Schematic representation of an absorption refrigeration cycle WHR system using main engine exhaust gas as heat source.

While the system described is that of a single stage absorption refrigeration WHR system, various modifications and alternative layouts can help improve the performance. These alternative layouts include double stage, cascade and hybrid absorption / compression systems. The technical performance of various absorption cycles is shown in **Table 5**, while absorption refrigeration costs are shown in **Table 6**.

Table 5 Characteristics and performance of absorption cycles, data originally synthesised in [43]

Cycle	T_{evap} [°C]	COP	Working Fluid	Ref
Single-stage cascade	- 30 to 5	0.25 - 0.55	NH_3 - H_2O	[44]
Double-stage cascade	- 20 to 0	0.17 - 0.31	H_2O - LiBr // NH_3 - H_2O	[75]
Double stage	/	0.29	H_2O - NH_3	[47]
Absorption / Compression	- 10	1	NH_3 - H_2O	[80]

Table 6 Absorption refrigeration costing elements, data gathered from [50]

Design	Heat Source	Cooling Capacity (kW)	Installed Cost (€/kW)	Maintenance 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 Fired	1155	1070	0.097
		3500	648	0.032

Adsorption refrigeration

A cooling effect is generated with adsorption refrigeration by leveraging the boiling point of a refrigerant at low temperature to extract heat from another working fluid, a similar working principle to absorption refrigeration discussed previously. The principal difference is that the refrigerant vapour is then adsorbed onto the surface of a solid sorption material, rather than absorbed into a liquid solution. The adsorbed refrigerant is then separated from the condensed phase using a thermal energy input during a process called desorption. Typical adsorption materials (so-called adsorbents) include [51] silica gel and metal-organic frameworks.

Additionally, seawater can be used as the working fluid which can result in its desalination during the consecutive adsorption/desorption process; the relatively high boiling point of sea water (compared to traditional refrigerants such as ammonia) however limits the minimum temperature reached from the cooling process to that of chilled water (0°C to 5°C). A schematic representation of a two-bed adsorption refrigeration system with desalination function [52] is shown in **Figure 5**.

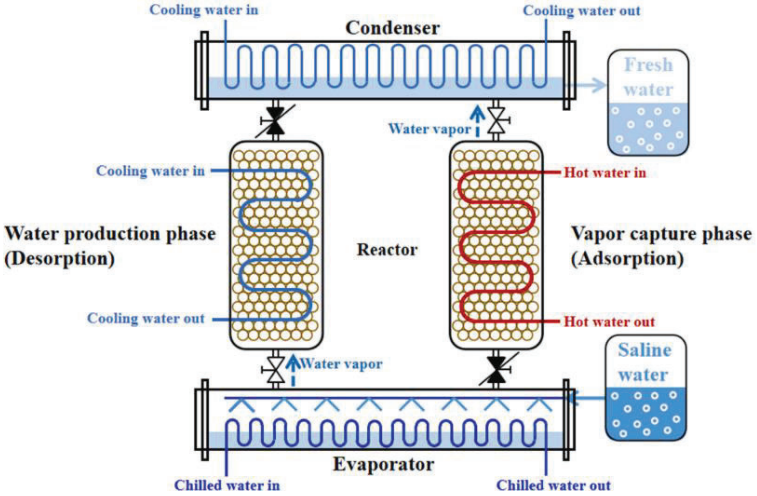

Figure 5 Schematic representation of two-bed adsorption refrigeration system [52]

Thus, this system can either be designed with a conventional refrigerant to generate sub-zero cooling, or with seawater as the refrigeration for chilling and desalination. The system shown in **Figure 5** is a two-bed system which is a rather simple configuration of this technology. Various modifications and more advanced configurations can be implemented to increase overall cooling power or rate of desalination. Three [53] and four [54] bed systems have been investigated, along with hybrid systems specifically designed for fishing vessel refrigeration [11] which combine adsorption refrigeration with conventional vapour compression systems. Adsorption refrigeration is a novel technology, thus techno-economic data is sparse. Costing elements for some adsorption chillers have been derived from analogous refrigeration technologies (absorption and vapour compression refrigeration) and are shown in **Table 7**. With the current state of the art, the maximum cooling power for adsorption chillers is around 100 kW.

Table 7 Cooling capacity and specific cost of various adsorption chillers.

Model	Cooling Power [kW]	Specific Cost [€/kW]	Ref
InvenSor LTC30 e plus	10 - 35	1,327	[55]
SorTech eCoo 2.0 Silica Gel IP20	16	1,188	[56]
Unnamed Silica gel / water adsorber	8	1,331	[57]

Isobaric Expansion Engines

Isobaric expansion engines (IEE) are a type of heat-to-mechanical power converter, based on a non-polytropic gas expansion process at theoretically constant pressure in a cylinder [58]. IEEs encompass various engine concepts such as Savery, Newcomen, and Watt pumps [59], Worthington direct-acting steam engines [60], and Bush thermo-compressors [61]. As seen from the provided examples, IEE is an old concept which has nonetheless received recent attention by technology makers due to the potential for useful work production from low temperature heat sources (as low as 40°C) and low temperature differences (ΔT = 30°C), albeit with low efficiencies compared to other heat to work conversion technologies [62]. The latter of the two examples, Worthington and Bush-type engines have generated most of the recent interest; the Worthington engine is represented schematically in **Figure 6** in the context of WHR, where it is assumed that marine exhaust gases are used to generate steam (in the EFB) that undergoes the isobaric non-polytropic expansion process in the IEE. At the beginning the cycle, steam inlet valve **6** is manually 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** pushes the liquid out of cylinder **2** through the self-acting outlet valve **9**.

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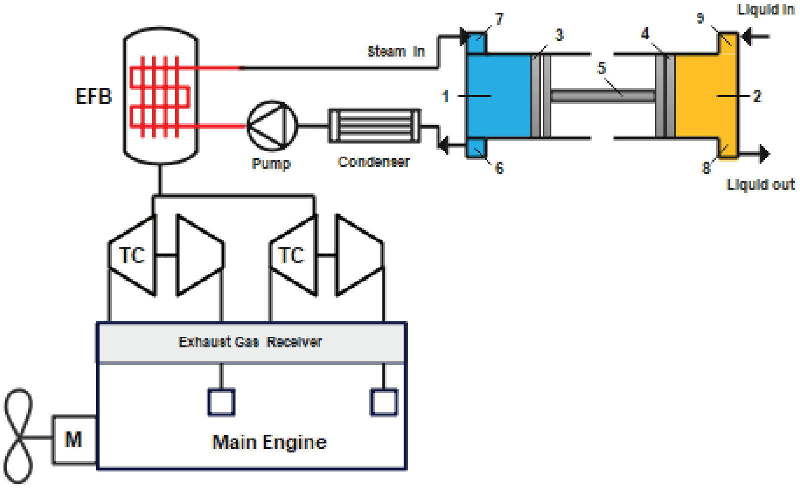

Figure 6 Schematic representation of the basic working principle of Worthington steam pump in the context of marine WHR.

When pistons **3** and **4** have fully displaced to the right-hand side, steam inlet valve **6** is closed, while liquid enters pumping cylinder **2** through the liquid inlet valve **8**, pushing piston **4** outwards and instigating the return motion of the engine stroke. Piston **3** displaces steam out of cylinder **1** through steam outlet valve **7** that is now opened until both pistons have fully moved to the left, thus completing the pumping cycle. It is assumed that the steam returning from the IEE is condensed (sea water used for cooling) and pumped back towards the EFB. The layout shown in **Figure 6** represents the simplest possible Worthington IEE. Extensive descriptions of more advanced IEE layouts can be found in [63]. For Worthington and Bush type IEEs, overall thermal efficiency can be found around 5%, for power deliveries below 1 kW, as shown in **Table 8**. The generated work can be used for a variety of on-board applications, such as powering pumps, compressors and other converters [58], or for water desalination [64]. However the simplest method may be to connect the IEE to a hydraulic circuit and generator [58].

Table 8 Performance characteristics of IEEs compared to thermal power pump (TPP). Data originally gathered in [62]**.**

	Cylinder Volume [L]	Cycle period [s]	Power [W]	Volumetric Power [W/L]	Efficiency [%]	Ref
TPP system	1.8	200	1	0.6	0.5	[65]
IEE-Bush	0.02	2.5	20	1200	6.4	[62]
IEE-Worthington	1	4	500	500	5.4	[62]

Thermal energy storage

Thermal energy storage (TES) is a technology designed to resolve the mismatch between heat availability and demand, particularly relevant for renewable thermal energy sources, namely solar, geothermal, and waste heat recovery. TES is classified into three distinct technologies [66], listed here in order of increasing complexity, cost, and energy storage density potential:

- Sensible TES (STES): heat is stored/released by increasing/decreasing the temperature of a solid or liquid [67]. STES materials include water, rocks, sand, molten salts, and metallic materials.
- Latent TES (LTES): heat is stored as the phase-change enthalpy of the melting/boiling process of a solid/liquid called phase change material (PCM). The reverse phase-change process is performed for discharge.
- Thermochemical energy storage (TCS): heat is stored/released as the reaction enthalpy of reversible exothermic/endothermic reactions. Typical thermochemical reactions for TCS include water sorption onto zeolite or other sorbents, hydration of inorganic salts, carbonation and oxide-reduction reactions.

The schematic representation of a thermal energy storage system integrated to a marine energy system is shown in **Figure 7**. TES is a passive WHR technology that doesn't directly convert waste heat to useful work but acts as a buffer to either store and release heat based on on-board demand or enable other WHR heat-to-X converters to operate with higher efficiency, such as power cycles.

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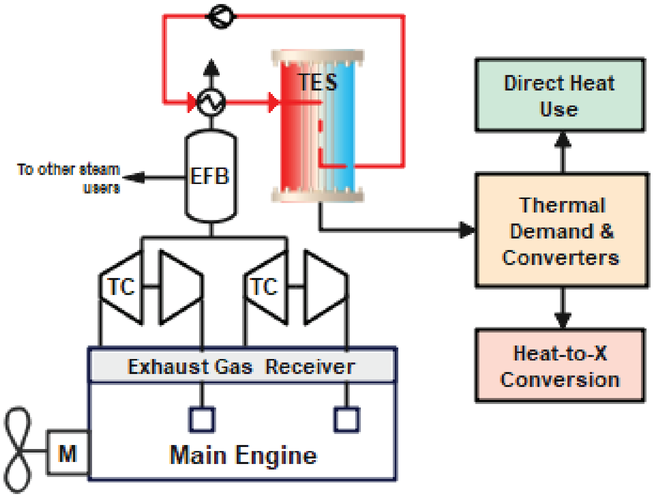

Figure 7 Schematic representation of the integration of TES to a marine energy system.

The system shown in the figure considers a single temperature level, with heat recovered from the exhaust gases. In real marine energy systems, TES has been envisioned for the storage of heat through a cascade of LTES systems with different PCMs each adapted to the temperature levels of the multiple onboard waste heat streams, potentially recovering 10% to 15% of fuel input as stored heat [68]; for the production of hot water on cruise ships to reduce by up to 80% fuel consumption in auxiliary boilers using a 1,000 m3 thermal oil-based STES [69]; for synergistically improving other WHR technologies, similarly to conventional WHR [70]. Excess heat stored in an LTES can be released at approx. 100°C to evaporate the working fluid in an on-board ORC [71]. An important design decision is how heat is transported to the TES and exchanged with the storage material. Typical techno-economic performance characteristics of various TES systems with these layouts are shown in Error! Not a valid bookmark self-reference.. STES generally displays low energy storage density (> 50 kWh/m^3), and TCS too low of a technological maturity, for realistic implementation in marine energy systems; thus, LTES can be considered as the most suitable TES sub-category for on-board WHR.

Table 9 Techno-economic performance of various TES systems, data originally synthesised in [72]**. ST: shell and tube, PB: packed bed, TT: tube-in-tank.**

Type	Material	Energy Storage Density [kWh/m^3]	Efficiency [%]	Volume [m^3]	Cost [€/kWh]	Ref
PB - LTES	$Li_2CO_3/K_2CO_3/Na_2CO_3$	66	80%	2	-	[73]
PB - LTES	$Li_2CO_3/K_2CO_3/Na_2CO_3$	115	61%	83,333	-	[74]
ST - LTES	Sodium Nitrate	-	-	77,161	65	[75]
ST - LTES	KOH	-	-	83,333	19	[76]
TT - LTES	Paraffin RT82	-	-	6	260	[77]
TT - LTES	Sodium acetate trihydrate	-	-	2,500	58	[78]

Conclusions

This article presented a systematic review of waste heat recovery technologies applicable to marine energy systems. The technologies were mainly characterised by their power capacity, efficiency / coefficient of performance, and specific investment cost. Furthermore, their applicability to marine energy systems for diesel engine WHR was discussed. It emerges from the review that:

- The turbine-driven heat-to-power technologies, i.e., turbocompounding systems and Rankine cycles, display the highest technological readiness level with market ready and proven systems, and highest potential power output each in the order of magnitude of at least 200 kW to 3 MW. These waste heat recovery technologies also have a high range of applicability since high electrical demand is likely regardless of vessel type and voyage.
- Kalina cycles typically show the same technical performance as Rankine cycles, but should still be considered as an unproven technology, with insufficient practical applications in conventional WHR let

alone marine waste heat recovery. Thermoelectric generation shows promising characteristics but low power outputs for individual modules severely limit economic viability.

- Through other technologies such as adsorption, absorption, and isobaric expansion engines, waste heat can be recovered and converted to other forms of useful work than electrical power. The suitability of the technology depends on the types of on-board energy demands which in turn depends on the vessel and voyage type. With their current technology readiness level however, only absorption refrigeration can deliver net power output in the same order of magnitude as the most powerful waste heat recovery technologies: 100 kW to 5 MW for absorption refrigeration, 8 kW to 35 kW for adsorption refrigeration, isobaric expansion engines are unproven beyond 1 kW.
- Thermal energy storage is in its own class of passive WHR technology, best used synergistically with other WHR technology to improve their performance by matching waste heat availability with on-board demands. Latent thermal energy storage is the best suited technology for on-board applications.

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Nomenclature

COP	Coefficient of Performance
IEE	Isobaric Expansion Engine
LTES	Latent Thermal Energy Storage
ORC	Organic Rankine Cycle
PB	Packed Bed
PCM	Phase Change Material
PTG	Power Turbine Generator
ST	Steam Turbine
STES	Sensible Thermal Energy Storage
STG	Steam Turbine Generator
ST-PT	Steam Turbine – Power Turbine
TCS	Thermochemical Energy Storage
TEG	Thermoelectric Generation
TES	Thermal Energy Storage
TT	Tube-in-Tank
WHR	Waste Heat Recovery

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