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Waste heat recovery from marine engines and their limiting factors: Bibliometric analysis and further systematic review

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ABSTRACT

To cope with present energy and climate crises, maximization of energy use becomes essential. Maritime transport is the core of international trade and the majority of vessels are equipped with marine engines for propulsion and power generation. This paper provides an exhaustive state of the art review on enhancing efficiency technologies based in waste heat recovery and applicable to marine engines. A bibliometric analysis followed by a systematic review based on the PRISMA 2020 approach is presented in order to identify current used systems, not implemented but available technologies and non-explored heat sources. From a wide query on Scopus and Web of Science databases, 576 results were obtained for the bibliometric analysis. Further selection of the most relevant journal articles gave a total of 35 studies, 30 original articles and 5 reviews, for the in-depth analysis. As a result, the organic Rankine cycle was identified as the most common technique for waste heat recovery. Cold energy recovery was found to be an innovative strategy but limited to vessels with LNG facilities. Despite the low representation in scientific literature, thermoelectric generators appeared to be a promising direction for future research. The recovery of low-grade waste heat was identified as a promising gap on the knowledge.

Acronyms

COP	Coefficient of Performance
DNV	Det Norske Veritas classification society
EEOI	Energy Efficiency Operational Indicator
EGR	Exhaust Gas Recirculation
GDP	Gross Domestic Product
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon refrigerant
IMO	International Maritime Organization
JCR	Journal Citation Reports
LNG	Liquefied Natural Gas
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
ORC	Organic Rankine Cycle
ppm	Parts per million
PT	Power Turbine
RO	Reverse Osmosis
SOEC	Solid Oxide Electrolyzer Cell
SRC	Steam Rankine Cycle
TDS	Total Dissolved Solids
TRL	Technology Readiness Level
WHR	Waste Heat Recovery
WoS	Web of Science

Introduction

Global warming is being recognized as one of the biggest challenges of our time (United Nations, 2020). Maritime transport contributes to climate change releasing greenhouse gasses (International Maritime Organization (IMO), 2021a). Over 95% of the world fleet use the internal combustion engine either for propulsion or power generation (Ishii, 1997; Lamaris and Hountalas, 2010). Most efficient diesel engines have a performance of less than 50%, which means a great amount of energy is dissipated, generally as thermal energy, into the environment. A two-stroke MAN12K98ME/MC engine studied before by several authors, with data from the manufacturer, transforms 49.3% of the energy contained in the fuel into shaft power. The remainder is dissipated in the

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form of heat through the exhaust gas, 25.5%, scavenge air, 16.5%, jacket cooling water, 5.2%, lube oil, 2.9% and heat directly radiated into the environment, 0.6% (Shu et al., 2013; Singh and Pedersen, 2016; Zhu et al., 2020). Díaz-Secades et al. studied a four-stroke medium speed engine and concluded that, while working at 100% load, the engine delivered 3000 kW of shaft power, which accounted for 40.54% of the energy contained in the fuel used. Thermal energy dissipated by the engine was over 59% of the fuel energy, being the exhaust gas, charge air and jacket cooling water the main receivers. The authors also determined that up to 5% of the chemical energy contained in the fuel was radiated from the block to the environment (Díaz-Secades et al., 2022). Due to this reason, and in order to reduce environmental impact of shipping and its operational cost, waste heat recovery (WHR) turns to be essential and therefore are the current object of study. While maximizing the recovery of energy and thereby reducing fuel consumption, waste heat recovery systems also contribute to harmful gasses emission reduction (Singh and Pedersen, 2016).

Several technological systems for the recovery of waste heat from marine engines are available, comprising different configurations as the majority of them can work either standalone or combined. Previous works examined each WHR system and explored some combinations that marked a trend in the field and established the waste heat sources on a marine engine. Shu et al. examined different WHR technologies and their application in two-stroke engines, analyzing economics and application feasibility. Power recovery by means of turbines, refrigeration systems, thermoelectric generation, steam Rankine cycles (SRC) and desalination were studied and determined that turbine and desalination systems are the more advantageous due to their maturity followed by the Rankine cycles, due to their convenience. Lastly, the authors stated that waste heat extraction for refrigeration purposes was a very interesting technology since exhaust gas, scavenge air and jacket cooling water, have all potential to be applied to an absorption refrigeration system, but lacked from application reports (Shu et al., 2013). Mondejar et al. conducted a review on the application of organic Rankine cycles (ORC) onboard vessels, concluding that the best heat sources for this technology were exhaust gas and jacket water. The authors mentioned a reduction of fuel consumption of up to 15% could be achieved (Mondejar et al., 2018). Zhu et al. reviewed bottom power cycles extending the work of Mondejar et al. and analyzing also Kalina and CO_2-based power cycles. The authors concluded that there is not a unique solution that fits all vessels: while steam Rankine combined with a Power Turbine (PT) system is recommended for power plants over 25 MW, ORC technologies fit better in smaller size vessels. In the case of CO_2-based power cycles, they needed to be combined with power plants of at least 5 MW and will operate in the transcritical or supercritical configuration. Finally, the authors stated that Kalina cycles were not recommended due to the toxicity of the water-ammonia mixture. Zhu et al. also considered as heat sources exhaust gas, scavenge air and jacket cooling water (Zhu et al., 2020). Apart from the already stated heat sources, no further developments were shown until heat radiated by the engine block was considered (Díaz-Secades et al., 2022). Therefore, there is a knowledge gap on the different WHR solutions, especially from the point of view of their potential to extract the lowest-grade waste heat. Consequently, this article aims to provide a wide review on WHR systems for marine engines discussed in the literature in recent years. First objective is to provide a scrutiny by quantitative methods, with a bibliometric analysis, followed by the second objective: a qualitative systematic review that adopts the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) approach (Page et al., 2021). Accordingly, the following questions were asked:

Q1: Which WHR systems are already applied or studied for its use on marine engines?
Q2: Is there any gap in the knowledge, in terms of current developed but not applied technologies or missing waste heat sources, that is worth to be explored?
Q3: Which of these proposed systems might provoke a breakthrough in the industry?

This paper is structured as follows. Section 2 presents the data collection procedure used for the study. Section 3 develops the methods applied in the bibliometric analysis of WHR technologies applied to marine engines along with energy-exergy efficiency studies and provides the results. Section 4 presents the systematic review of journal articles, focused on the WHR systems studied in the literature. Section 5 provides concluding remarks and a discussion about research trends and future works.

Data collection procedure

In this section, the data collection procedure applied for the bibliometric analysis and further systematic review is presented. Data for the review was collected according to the protocol illustrated in Table 1.

As described by Elsevier, Scopus and ScienceDirect use two different databases but Scopus indexes nearly the entire ScienceDirect database. Thus, a search carried out only in Scopus was considered valid (Elsevier, 2018).

An initial query with the keywords from Table 1 along with Boolean operators and wildcard characters to widen the search was done. The query was chosen because of the relevance of the terms and looking for different expressions that not exactly have the same meaning but refer to the same topic. A temporal restriction was applied to articles published from 1998, since Kyoto protocol was signed on Dec 11th 1997, to the present. This way literature published during the last 25 years was retrieved. This initial search on the selected databases resulted in a list of 1049 studies. From these obtained results, only journal articles and conference papers published in English language were evaluated, excluding Notes and Book Chapters which resulted in 908 studies. The exclusion of literature nonrelated to the subject area of interest resulted in 576 documents. In addition, any study where coal was considered was excluded from the search since modern merchant vessels are equipped with internal combustion engines that are not able to burn it. From this final query, the systematic search used for this study was carried on June 6th, 2022.

Final query: (TITLE-ABS-KEY (mari* AND engine) AND TITLE-ABS-KEY (waste AND heat AND recove*) OR TITLE-ABS-KEY (e?ergy AND efficiency)) AND PUBYEAR > 1997 AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “cp”)) AND (LIMIT-TO (LANGUAGE, “English”)) AND (EXCLUDE (SUBJAREA, “MATH”) OR EXCLUDE (SUBJAREA, “CENG”) OR EXCLUDE (SUBJAREA, “PHYS”) OR EXCLUDE (SUBJAREA, “SOCI”) OR EXCLUDE (SUBJAREA, “COMP”) OR EXCLUDE (SUBJAREA, “EART”) OR EXCLUDE (SUBJAREA, “CHEM”) OR EXCLUDE (SUBJAREA, “AGRI”) OR EXCLUDE (SUBJAREA, “ARTS”) OR EXCLUDE (SUBJAREA, “BIOC”) OR EXCLUDE (SUBJAREA, “ECON”) OR EXCLUDE (SUBJAREA, “MEDI”) OR EXCLUDE (SUBJAREA, “PHAR”)) AND (EXCLUDE (EXACTKEYWORD, “Coal”))

Expert judgement process

Table 1
Review protocol applied to the data collection.

Subject	Description
Databases	Elsevier (Scopus), Web of Science
Keywords	Marine engine, Waste heat recovery, Energy / Exergy Efficiency
Search field	Title, abstract, keywords
Publication type	Journal articles and Conference proceedings
Publication language	English
Time interval	1998 - 2022

In order to mitigate the risk of bias of this study, especially for the systematic review section, experts in the field provided additional assessment. Expert judgment is a useful validation method that relies on information and evidence, rather than opinions (Kaplan, 1992; Skjong and Wentworth, 2001).

The selection of the experts for this study was made according to the following criteria:

- Extensive theoretical knowledge and professional experience in the related field.
- Experience in performing judgements and making decisions based on evidence.

Four people composed the team of experts: two internal and two external. Internal experts are professors at University of Oviedo, specialized in marine engines and energy efficiency. External experts were a Principal Surveyor from the classification society Det Norske Veritas (DNV) specialized in newbuilding and a Chief Superintendent of Ership shipping company, both not related to the study as this helped to attenuate the risk of bias. All experts worked independently of each other during the review process and reported to the corresponding author of the article.

Bibliometric analysis

A bibliometric analysis is a useful tool that helps mapping the cumulative scientific knowledge in a specific field and a method to organize and structure large volumes of data. The main advantages of this method is that the created overview allows a quick identification of knowledge gaps (Donthu et al., 2021). Conversely to systematic reviews where the scope of the study becomes very narrow, bibliometric analyses relies on quantitative techniques, which greatly mitigate the risk of bias.

This section contains a bibliometric analysis of the 576 articles and conference papers related to waste heat recovery and energy-exergy efficiency on marine engines.

Methods for bibliometric analysis

For the bibliometric analysis of the selected studies, a science mapping technique was selected. This method examines how research terms are related and affect to the intellectual interactions among them. Later, this technique was combined with clustering network analysis (Cobo et al., 2011).

Distributions by year of publication, keywords, journal, technology, first author and their country of origin were observed. A mixed approach was used where keywords were analyzed with co-occurrence and co-authorship methods, with the help of the VosViewer software. Descriptive statistics were applied to determine the distribution of years and journals of publication. Table 2 describes the entire framework used for the bibliometric analysis.

Distribution by year of publication

The yearly distribution of the selected publications (1998 to 2022) is presented in Fig. 1. Before 2007, it is evident that there was very limited academic interest on WHR techniques and marine engine efficiency but 2008 marked the beginning of an ascendant trend in publication. Another increase occurred in 2009, with a more or less stable number of articles until 2015. Thereafter, the annual number of articles increased again, from 33 publications in 2015 to 48 publications in 2016. The number of publications in the research domain had its peak in 2020, with 75 publications. The second year with highest number of articles published was 2021, with 53 publications. At the time this review was made, 20 articles were published, which forecasts a similar number of publications in 2022 to the previous year.

Table 2
Methodological framework proposed for the bibliometric analyses of the selected literature.

Aspects of analysis	Method
Year of publication	Descriptive statistics
Keyword	Co-occurrence analysis and clustering
Journal of publication	Descriptive statistics
Waste heat recovery technology	Co-occurrence analysis and clustering
First author	Co-authorship analysis and clustering
Country of first author	Co-authorship analysis and clustering

Distribution by keyword

Science mapping technique with a co-occurrence analysis was used to evaluate the keywords of the selected 576 publications related to WHR and energy-exergy efficiency on marine engines. Meanwhile some other science mapping methods focus on the publications themselves, co-occurrence analysis targets words to examine the actual content of the publication (Donthu et al., 2021). In this case, the keywords of selected publications were analyzed and represented as items, where the size of each item corresponds to the number of occurrences and thus, an evaluation of their relationship is presented. As shown in Fig. 2, 60 items were identified as critical keywords of publications addressing marine engines, waste heat and efficiency. Since the whole set of studies reviewed accounted for 5408 keywords, Fig. 2 only represents relevant items with more than 25 occurrences in the selected 576 publications. The most frequently occurring items were 'Marine engines' (282 occurrences) and 'energy efficiency' (208 occurrences), followed by 'waste heat' (182 occurrences), 'diesel engines' (170) and 'ships' (157 occurrences). The links between the items show the connections between each keyword so terms that are commonly found together and have stronger links, are represented by thicker lines.

The co-occurrence analysis was assembled into three clusters. Terms inside a cluster have stronger links to one another than with terms in other clusters (van Eck and Waltman 2007). This additional network analysis of the connected terms enables an expert interpretation of emerging narrative patterns in the research domain and can be used to forecast future research directions in a field. From the results shown in Fig. 2, the authors, who are familiar with the research domain through earlier work in the selected topics, and through the data collection procedure explained in Section 2, aimed to provide a tentative indication of future lines of research.

In Fig. 2, publications that belong to the red cluster can be considered to represent a plausible narrative pattern focusing on waste heat utilization from diesel engines, related to a clear thermodynamic approach, especially steam Rankine and organic Rankine cycles along with thermoanalysis. The focus on these methods could be associated with a previous knowledge on steam turbine power plants and the use of exhaust gas as the main source of waste heat from the marine engine. Publications related to the green cluster can be understood to represent a narrative pattern addressing the impacts of climate change and its relationship with maritime transportation, regulations and greenhouse gas emissions. At the same time, topics on this cluster are closely related to fuel consumption and fuel economy. The blue cluster contains what seemed to indicate a pattern that focuses on non-conventional or more industrial focused applications like turbomachinery (with both gas and steam turbines) along with steam and combined cycle power plants. In addition, the production of electricity from WHR systems is strongly related to this cluster.

On the other hand, an analysis of the temporal distribution of the different topics resulted of special interest since power generation and WHR technologies in the maritime industry have changed over the years (Fernández et al., 2017). In Fig. 3, co-occurrence analysis by keywords was used to present the temporal trend of published topics in waste heat recovery from marine diesel engines. Since publications focused on waste heat recovery on marine engines before 2008 were residual, the

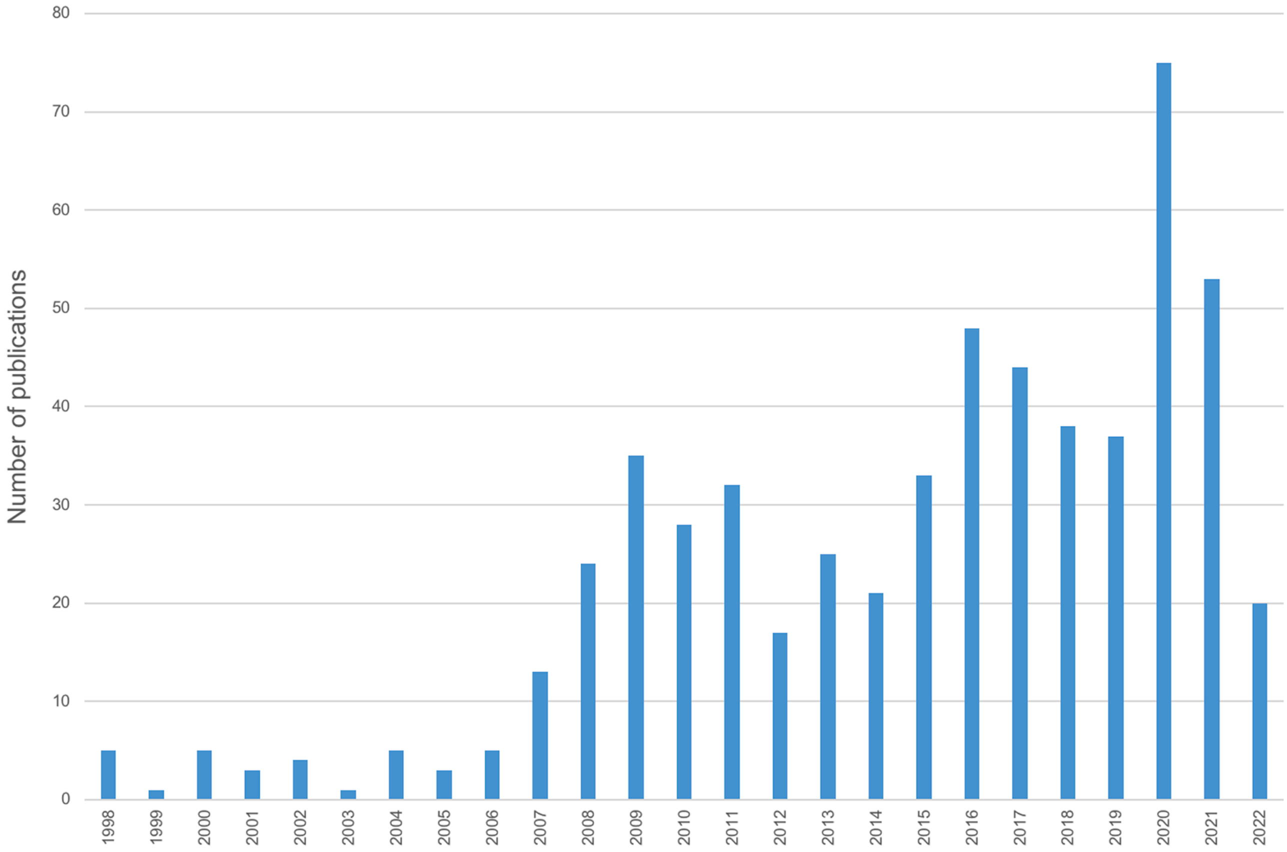

Fig. 1. Distribution of publication (articles and conference papers) by year of publication from 1998 to 2022. $N = 576$.

temporal analysis presented in Fig. 3 only accounts for publications from 2008 onwards. Recently, and due to the Paris agreement, researchers have increasingly paid attention to energy efficiency and waste heat recovery. Initial publications focused on turbines and its different technologies in which cogeneration and combined cycles were a significant development. More recently, the focus shifted to ORC, the extraction of waste heat from cooling water and the combination of WHR with emissions control systems, which are significant topics related to marine diesel engines.

Distribution by journal

The selected 576 publications in the identified data sample were published in 95 different journals and 84 conference proceedings. Looking for in-depth studies, conference proceedings were excluded from further analysis on this part of the bibliometric analysis. Among the 95 journals studied, 60 journals (63.16%) published only one article on the topic; 12 journals (12.63%) published two publications and 23 journals (24.21%) published three or more publications. The wide distribution of publications on the studied journals indicates that waste heat recovery and efficiency on marine engines are very interdisciplinary research domains, which are usually approached by a variety of research communities with common interests.

Inside the 95 journals present on this study, 338 articles were found. Table 3 lists the top 20 journals related to the field of study, sorted by number of publications. The table also lists the subject category of the journal, retrieved from the 2020 edition of Journal Citation Reports (JCR). The JCR index is made by Clarivate and provides information about academic journals, including their impact factor. This was done with the aim of giving an idea of the types of research published in these journals in relation to the topic of discussion.

Five top journals account for 36.09% of the total of articles analyzed on the studied topic. This shows that there are several journals with a more specialized focus on energy and thermodynamic processes, which take a leading role in developing the techniques and procedures on this research field.

Also, Table 3 reflects that there is a mixture of journals addressing environmental aspects, engineering, thermodynamics and oceanography sciences. On the lower half of the table, some of the publishers were found to be journals not indexed on the Journal Citation Reports so no *Subject* information was retrieved. Those were marked with an asterisk. According to Clarivate, there are several reasons that explain why a journal is not indexed on the last JCR (Clarivate, 2022):

- The journal ceased publication, or the title is no longer being indexed in the Web of Science Core Collection.
- A journal can be excluded from JCR despite its inclusion in Web of Science Core Collection due to excessive self-citations.
- Also, journals can be excluded from appearance in JCR if coverage of journal issues necessary for the compilation of citable item counts is incomplete.

Furthermore, some excluded journals were indexed on previous editions of the Journal Citation Reports but no present on the 2020 index. According to Clarivate: “***Journals dropped from coverage** prior to the release of that year’s Journal Citation Reports will not appear in the release. Since previous Journal Impact Factors are not considered valid except for historical comparison with current Journal Impact Factors, prior Journal Impact Factors for these journals are not included.*” (Clarivate, 2022). This argument will be later applied to the systematic literature review as an exclusion criterion in order to warrant that the selected articles provide the maximum quality of research.

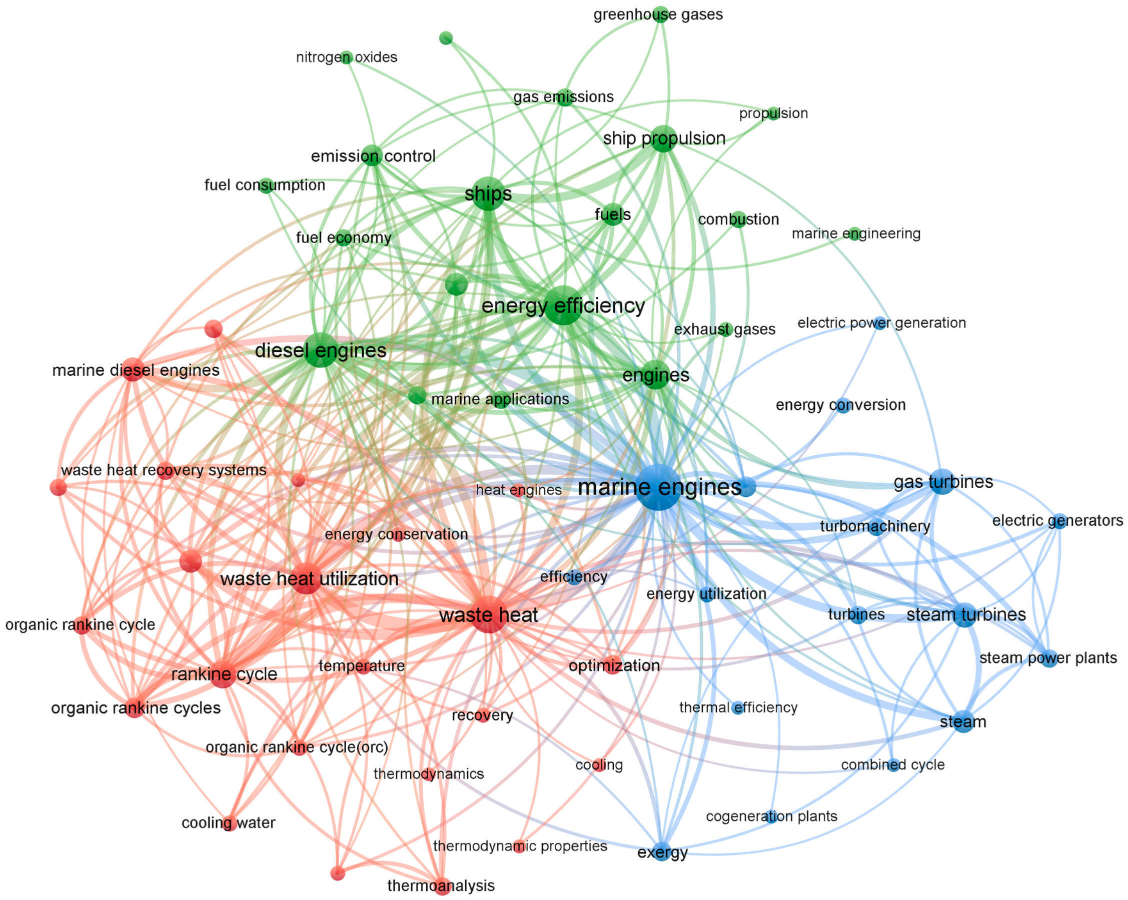

Fig. 2. Network visualization of co-occurrence analysis by keyword in the 576 publications related to Waste Heat Recovery on marine engines from 1998 to 2022, created by VosViewer.

Distribution by technology

Prior to the in-depth analysis conducted in the systematic review, a preliminary co-occurrence study was done in order to distinguish the most prominent waste heat recovery technologies. In Fig. 4 the results of this analysis are shown. The main keywords related to waste heat recovery systems in the 576 publications studied were related to turbines (gas and steam) and Rankine cycles (both conventional and organic) with 172 and 155 combined occurrences, respectively. Twenty-three heat recovery systems were identified and appear in Fig. 4 network where are divided in five clusters. The most prominent group, in red, is formed by Rankine and organic Rankine cycles plus heat exchangers, liquefied natural gas, evaporation and cooling. All of them are already established technologies, which had a major number of publications in the past literature. The second cluster, in green color, groups steam and gas turbines with combined cycles, fuel cells and refrigeration, also established technologies but generally studied separately from the systems in the first cluster. The third cluster by importance is represented in yellow and related to less implemented technologies as thermoelectric power generation, low-pressure turbines and Kalina cycle. Finally, two smaller clusters appear: the blue bundle groups absorption refrigeration, desalination, supercritical CO_2 and Brayton cycles while purple cluster is formed by exhaust gas recirculation, adsorption and cogeneration. From this preliminary analysis it can be observed that there are few waste heat recovery technologies, steam Rankine, ORC and turbines that have been massively studied. The three named technologies account for 327 occurrences while the lesser studied systems, blue and purple clusters together, have a total of 74 occurrences.

Distribution by author

In order to recognize the most noticeable authors related to waste heat recovery in marine engines, a co-authorship study related to the name of the first author was conducted. A total of 1521 different authors appear in the 576 publications studied so a first filter was applied before the co-authorship analysis: only authors with at least three publications and five citations per publication were considered. This exclusion criteria was set up so authors with singular publications in the topic were excluded as they would not be considered experts. The minimum number of citations was taken from an average of the median citations of the four main publishers, according to JCR data: Energy Conversion and Management with a median citation of 8 per article, Energy with 6 citations per article, Applied Thermal Engineering with 4 and Ocean Engineering with a median of 3 citations per article. Eight different clusters are shown in Fig. 5, which correspond to the related groups of researchers working on the topic.

As it can be seen in Fig. 5, eight non-related clusters appeared on the co-authorship analysis. This indicated that several authors collaborate in groups but those groups do not exchange knowledge or researchers with each other. Two prominent research groups are found: the first, in green, is leaded by Ouyang and composed of Chinese authors. The majority of this group are researchers from either the College of Mechanical Engineering at Guangxi University or the School of Mechanical Engineering at Southeast University. In second place, a group represented in red and leaded by Hagling and Larsen is composed of European authors that come from countries like Sweden and Denmark. In blue color, a third smaller but still relevant group is formed by Shu et al.

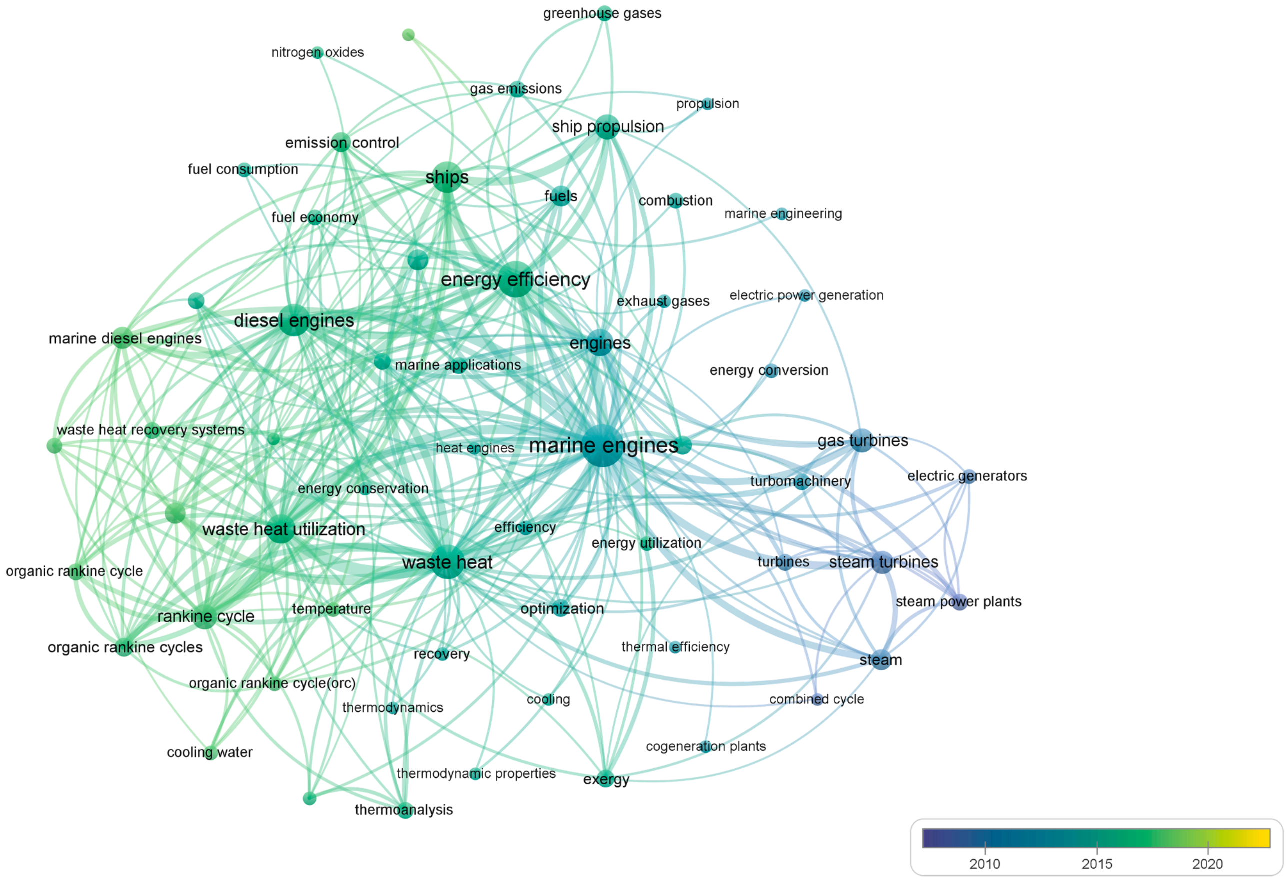

Fig. 3. Overlay visualization of the temporal evolution of keyword co-occurrence analysis in the 576 publications regarding Waste Heat Recovery on marine engines, colors represent the average year in which keywords appeared. Created by VosViewer.

Distribution by country

The last aspect observed on the bibliometric analysis used the science mapping procedure with the co-authorship analysis. This process examines the interactions among the different researchers of a scientific field. As science in general is reaching a high level of complexity and the WHR field of study in particular needs of abundant infrastructures in order to carry out experimental research, collaboration among authors with different affiliations is becoming common. In this part of the analysis, the country of origin of the first author of each published article and conference proceedings was observed. Fig. 6 shows the results of a co-authorship analysis used to map cooperation among countries for the 576 publications related to waste heat recovery and marine engines from 1998 to 2022. The countries of the authors are represented on the figure as items, where the size of each item corresponds to the number of publications originating from each country. The links between items indicate collaborations between countries, where the link width is associated with the intensity of that collaboration. The selected 576 publications studied came from 44 different countries.

Out of the identified nations, major contributors to research on WHR on marine engines were identified. In order to name a country as a major contributor, the country had to have at least five publications on the topic. At the time of the analysis, the most productive countries on the topic were: China (90 publications), the United States of America (54 publications), Italy (46 publications), followed by the United Kingdom (39 publications), India (29 publications), and Sweden and South Korea (25 publications each).

In Fig. 6, links between nodes represent the existence of collaborative research activities between countries, with thicker lines indicating stronger collaboration. The clustering colors of countries indicate that collaborations between these entities in terms of academic publishing are stronger than with entities from other clusters. While no very firm geographical conclusions can be made from this analysis, clustering indicates that Asian countries work comparatively closely together but in two separate groups with China leading the green cluster where also collaborate Hong Kong, India, Malaysia, Singapore and Vietnam. The red cluster gathers also Asian nations like South Korea, Japan, Taiwan, Bangladesh, Russia plus two European countries: Spain and Ukraine. On the West, the United States of America and Italy present the strongest collaboration with less intensive input from other technological developed countries like the United Kingdom, Germany, Sweden and Denmark. Since collaboration on this West alliance is not that intensive, items on Fig. 6 appear in different colors.

Once major contributor nations were identified, a further analysis was done in order to understand how the largest contributors interact and collaborate with other countries. Fig. 7 shows the prevalent relations that China has with other major contributors. In addition, in Figs. 8 and 9, the networks of the other two largest contributor nations, the US and Italy, are shown.

From Figs. 6 to 9, it can be appreciated that countries highly technological developed are the most scientifically productive in the research area. These countries (China, the United States of America and Italy) spent in 2018: 2.18%; 2.83% and 1.39% of their yearly gross domestic product (GDP), respectively, in research and development (World Bank, 2021). Also, according to the United Nations Conference on Trade and Development (UNCTAD), China and the United States of America were the two largest trading nations in 2020 (United Nations Conference on Trade and Development, 2020), which can explain their particular interest in maritime transportation.

Other highly productive regions (the United Kingdom, India, Sweden

Table 3
Top 20 journal sources related to waste heat recovery on marine engines from 1998 to 2022. $N = 229$.

Ranking number	Journal	ISSN	No. of publications	Subject
1	Energy Conversion and Management	2590–1745	46	Thermodynamics; Energy & fuels; Mechanics.
2	Energy	0360–5442	30	Energy & fuels; Thermodynamics
3	Applied Thermal Engineering	1359–4311	18	Energy & fuels; Thermodynamics; Engineering, mechanical; Mechanics
4	Ocean Engineering	0029–8018	15	Oceanography; Engineering, civil; Engineering, ocean; Engineering, marine
5	Journal of Cleaner Production	0959–6526	13	Engineering, environmental; Environmental sciences; Green & sustainable science & technology
6	Journal of Marine Science and Engineering	2077–1312	13	Oceanography; Engineering, marine; Engineering, ocean
7	International Journal of Energy Research	1099–114X	12	Nuclear science & technology; Energy & fuels
8	Applied Energy	0306–2619	11	Energy & fuels; Engineering, chemical
9	Motor Ship	0027–2000	10	*
10	Journal of Engineering for Gas Turbines and Power	1528–8919	9	*
11	Polish Maritime Research	2083–7429	8	Engineering, marine
12	Advanced Materials Research	1662–8985	6	*
13	Journal of Marine Engineering and Technology	2056–8487	6	Engineering, marine
14	Naval Architect	0306–0209	6	*
15	Brodogradnja	1845–5859	5	Engineering, marine
16	Environmental Science and Pollution Research	1614–7499	5	Environmental sciences
17	Applied Mechanics and Materials	1662–7482	4	*
18	Journal of Mechanical Science and Technology	1976–3824	4	Engineering, mechanical
19	Maritime by Holland	2211–3444	4	*
20	MER - Marine Engineers Review	0047–5955	4	*

and South Korea) have also important economic interests in the global maritime industry, which may explain their active involvement in the research on marine engines. For the 2022–2023 biennium, all these countries have been elected as IMO Council Members. Table 4 summarizes named countries during the latest IMO Assembly (International Maritime Organization (IMO), 2021b):

Systematic review on waste heat recovery technologies applied to marine engines

After the quantitative bibliometric analysis was completed, a further filtering was conducted for the systematic review. For this analysis, the PRISMA 2020 approach was chosen to help providing a methodological approach to a wide-ranging field (Page et al., 2021).

The scope of this detailed analysis of literature is limited to waste heat recovery on marine engines. The specific aim is to develop a high-level qualitative synthesis of the state-of-the-art knowledge on WHR systems for marine engines.

Based on the data collection procedure outlined on Section 2.2, a further filtering was done. In order to narrow down the literature for this systematic review, the PRISMA 2020 flow diagram for new systematic reviews which included searches of databases, registers and other sources was used. Fig. 10 shows the PRISMA flowchart with the search and filtering conducted.

Study selection results

Using the final query described on Section 2.2, a systematic search was done and 576 results were found. Duplicates were eliminated and from there, the following exclusion criteria were applied:

- Incomplete author information.
- Publications on conference proceedings.
- Papers published on journals not indexed on the Journal Citation Reports 2020.

During the abstract screening, the following inclusion criteria were followed:

- Literature directly related to marine diesel or dual-fuel engines.
- Thermodynamic oriented studies, excluding economic oriented papers.

In order to reduce the bias of the study, a previous bibliometric analysis based on science mapping was conducted. After the complete set of studies was analyzed based on whether they fit into the scope of our research, 35 studies were selected to be reviewed in depth. A simplified breakdown of the selection process can be seen in Fig. 10.

Initially, 576 journal articles and conference proceedings were found during the “Identification” process by using the final query described in Section 2. The “Screening” process reduced this number to 338 articles. After filtering and applying the exclusion criteria and the inclusion of additional articles manually searched, 35 publications divided in 30 full articles and 5 review papers were analyzed. A synthesis of the selected and analyzed studies is presented in Table 5, which summarizes the full results of the PRISMA search, was sorted by year of publication.

The temperature range where each WHR system works is essential to know as the quality of the heat and its level of exergy differs. Musharavati and Khanmohammadi proposed to categorize WHR into three groups, attending to the temperature range: low temperature (less than 230 °C); average temperature (from 230 °C to 650 °C) and high temperature (above 650 °C) (Musharavati and Khanmohammadi, 2021). In Table 5, the column *Temperature range* has been filled according to their criteria but exchanging “Average” for “Medium” as authors found the term more appropriate. Also, the term “Cold” has been included for those cases where, when working with dual-fuel engines, spare cold energy from the vaporization of liquefied natural gas (LNG) was recovered.

Another interesting feature found while reviewing the set of papers is the manner each study has been conducted and how data was collected.

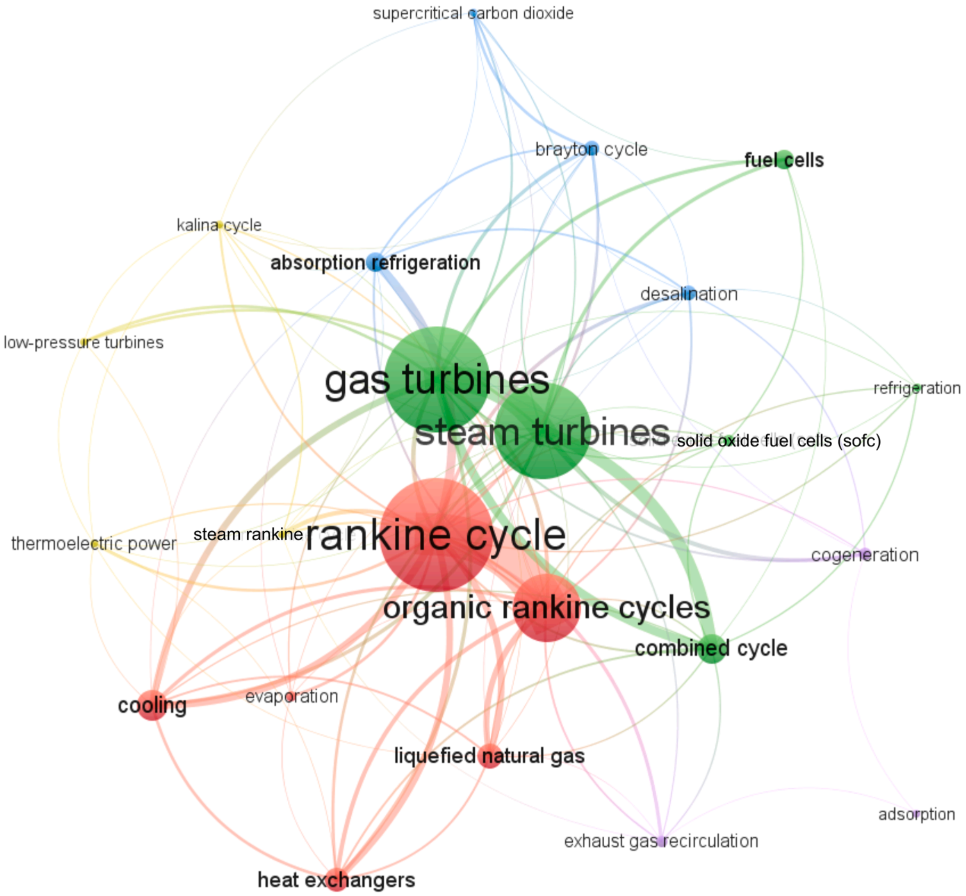

Fig. 4. Network visualization of co-occurrence analysis by waste heat recovery technology in the 576 publications related to Waste Heat Recovery on marine engines from 1998 to 2022, created by VosViewer.

Some papers presented a case study while others relied on manufacturer's data or marine simulators. Table 6 shows the relationship between each study, the heat source used, type of investigation done, and efficiency attained. Table 6 only reflects original works and therefore, reviews are omitted.

Waste heat recovery technologies

The majority of WHR systems studied relied on thermodynamic cycles to extract waste thermal energy, mainly from the exhaust gas as this is the best quality heat source. Also, other heat sources as scavenge / charge air, jacket water and lubrication oil have been object of study. Furthermore, the possibilities of thermoelectric conversion were investigated. In Fig. 11, the distribution of WHR systems found in the literature search is shown.

Rankine cycle

The Rankine cycle is the basis of power cycles converting thermal energy into mechanical work. A typical Rankine cycle comprises at least four components: a boiler (or an evaporator), a turbine, a condenser and a pump (Dumont and Lemort, 2022). The working fluid circulates through the circuit, condensing and evaporating continuously. Depending on the temperature range of the heat source, different working fluids can be used (Singh and Pedersen, 2016).

Steam Rankine

In a conventional steam Rankine cycle, water is used as working fluid. Inside of a boiler, water vaporizes forming pressurized steam, which is later expanded, producing work. In this way, the chemical energy stored in the fuel eventually becomes mechanical shaft work, generally used to drive an electric generator. In WHR systems, the source of energy is not the fuel directly but the thermal energy that the main system delivers as a residue. After expansion, the wet steam is transformed into liquid in the condenser. Refrigeration of the condenser is usually done by water, which is common in other marine applications as well. The pump returns the condensed water to the boiler using a minor amount of energy since the working fluid is entirely liquid. In Fig. 12a schematic diagram along with a T-S diagram of the thermodynamic cycle is shown.

Due to the shape of the water T-S diagram, steam Rankine works with a wet fluid. This means that, if the steam is expanded when it is in saturated vapor form, the expander will receive wet steam (with a humidity value over 10%). This can be detrimental for the machinery, causing preemptive mechanical wear due to erosion. To avoid this problem, superheat is usually applied to steam Rankine cycles: the steam is heated in the boiler until it becomes superheated enough to expand without crossing the saturated vapor frontier. In terms of efficiency, this technique is unfavorable as a higher amount of thermal energy needs to be employed in order to raise the temperature of the steam further into the superheat area. When designing a steam Rankine system, a balance between superheat energy needs and maintenance costs needs to be calculated. Also, evaporation pressure of the cycle is a limiting factor: the higher the evaporation pressure, the less latent heat is needed for vaporization. Due to this, it could be interesting to raise the pressure that the pump delivers in order to vaporize the working liquid at higher pressures, where less energy is required for the task.

In the marine industry, steam Rankine cycles have been used in the past decades for main propulsion and auxiliary power generation on LNG vessels (Mrzljak et al., 2017). Diesel engines are the preferred

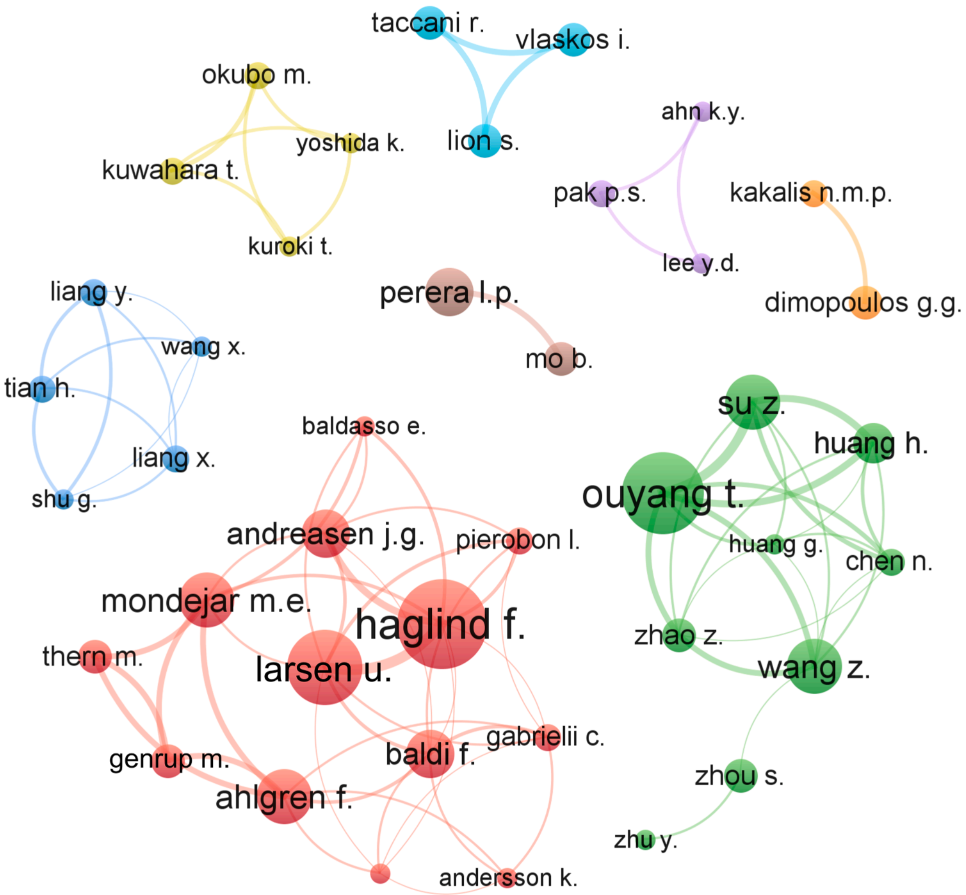

Fig. 5. Network visualization of co-authorship analysis by name of first author in the 576 publications related to Waste Heat Recovery on marine engines from 1998 to 2022, created by VosViewer.

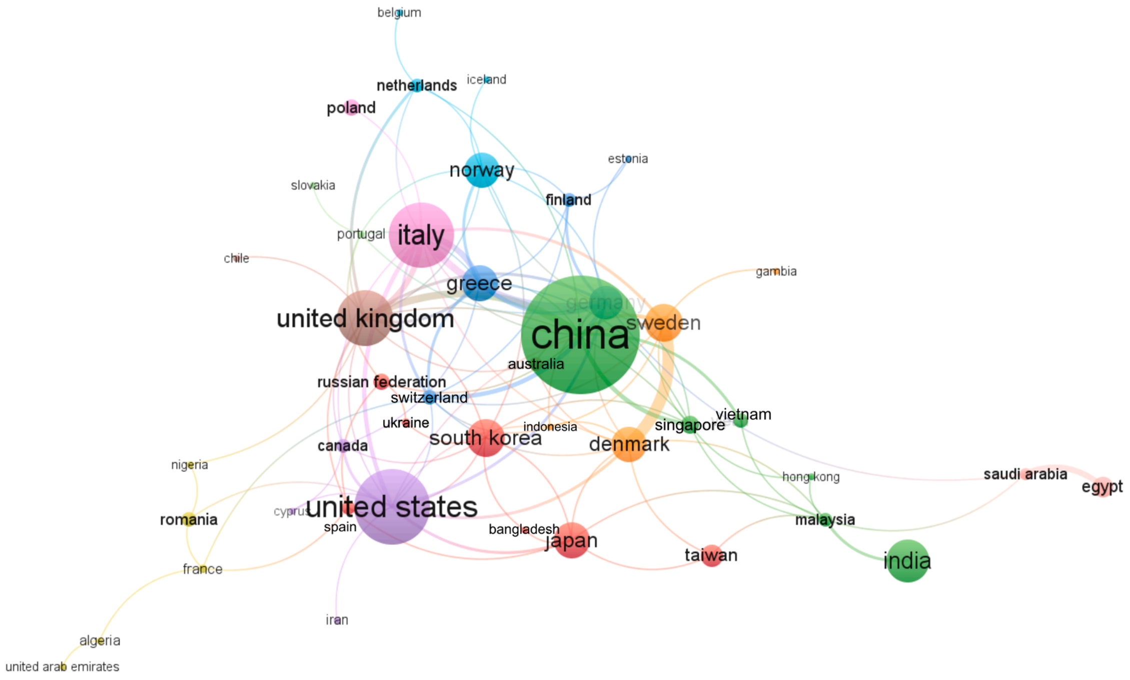

Fig. 6. Network visualization of co-authorship analysis by country in the 576 publications related to Waste Heat Recovery on marine engines from 1998 to 2022, created by VosViewer.

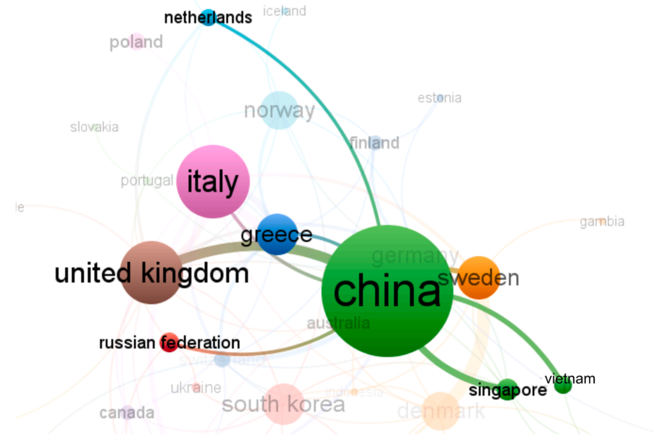

Fig. 7. Network visualization of co-authorship collaboration of China, the largest contributor to the topic, with other countries. Created by VosViewer.

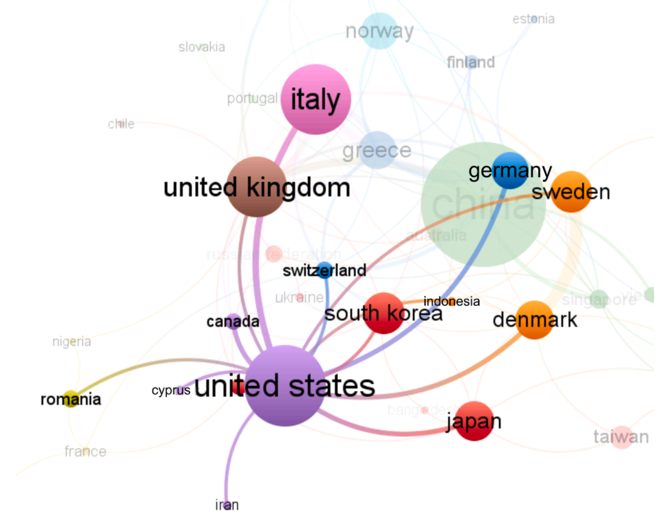

Fig. 8. Network visualization of co-authorship collaboration of United States, the second largest contributor, with other countries. Created by VosViewer.

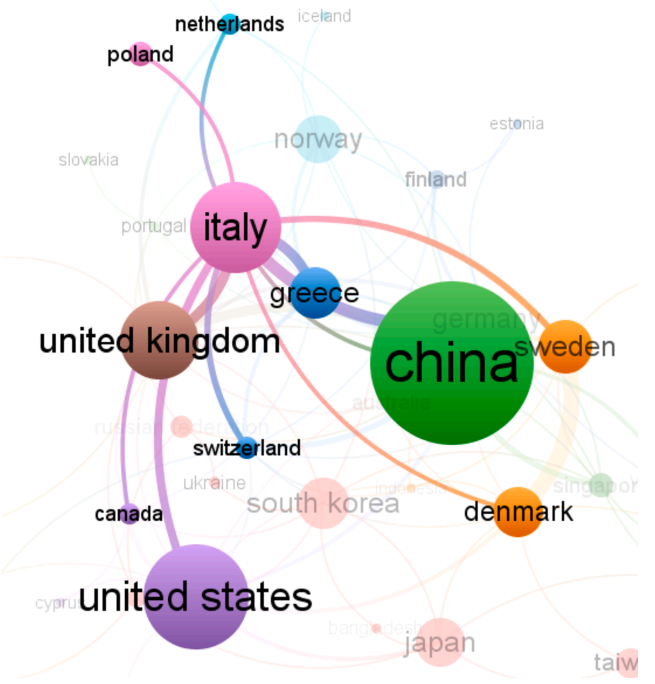

Fig. 9. Network visualization of co-authorship collaboration of Italy with other countries. Created by VosViewer.

Table 4
Elected nations to be members of the IMO Council for the 2022–2023 biennium.

Category (a): States with the largest interest in providing international shipping services	Category (b): States with the largest interest in international seaborne trade
China United States Italy United Kingdom South Korea	India Sweden

technology for marine propulsion nowadays, but steam Rankine cycles are still a feasible option for WHR systems (Singh and Pedersen, 2016). The steam Rankine cycle is a very versatile thermodynamic power cycle that can be implemented standalone or as a part of a larger WHR system. Ma et al. proposed a system where the majority of the waste heat from the exhaust gas of the marine engine equipped with bypass valve was recovered by means of a Rankine cycle. A power turbine generator complemented this system in order to extract energy from the exhaust gas that bypassed the engine turbo-compressor (Ma et al., 2012). A cogeneration system where a Rankine cycle recovered waste heat from a Wärtsilä-Sulzer two-stroke engine was studied by Liang et al. The excess of heat released by the condenser of the Rankine cycle was used in an absorption refrigeration cycle with a notable increase in exergy efficiency, from 25.38 to 46.79% (Liang et al., 2014). Another way to maximize the recovery of waste thermal energy is the combination of a steam Rankine cycle with an ORC. Since the vaporization temperature of the different working fluids used in each cycle is different, different heat grades can be recovered. Liu et al. studied the combination of a conventional Rankine combined with an ORC with cyclopentane as working fluid versus the use of a dual pressure ORC to recover energy not only from the higher quality exhaust gas source but also from the jacket cooling water (Liu et al., 2020a). A further analysis was carried by the same authors, including this time an absorption refrigeration cycle that recovered exhaust gas waste heat with a steam Rankine cycle combined with an ORC. In this case, jacket cooling water was employed as the water source for the steam Rankine cycle and also as a heat source for the absorption refrigeration cycle, adding 2940 kW of cooling capacity to the system (Liu et al., 2020b). The use of jacket water cooling as the working fluid presents the advantage of a lighter system since the working fluid is already onboard, but also limitations: first, the pressurization of the water will be limited, unless an extra pump is installed, so the implementation of a higher vaporization pressure to decrease the latent heat needed might not be possible. Furthermore, jacket water cooling usually has a larger amount of dissolved solids than typical boiler water, which can be damaging to the machinery. Qu et al. presented a combination of a steam Rankine and an ORC with a power turbine in order to recover the waste heat contained in the exhaust gas that has bypassed the turbo-compressor and thus, has not been expanded. With this configuration, 1079.1 kW of power were recovered (Qu et al., 2021). The biggest limiting factor that the steam Rankine cycle presents when used in a WHRS is that the technique is optimized to extract high to medium-grade waste heat, so it is only applicable to the recovery of thermal energy from the exhaust gas.

Organic Rankine

Due to the main disadvantage that the conventional steam Rankine cycle presents, the temperature needed on the heat source has to be relatively high for the marine engine waste heat, the use of a Rankine

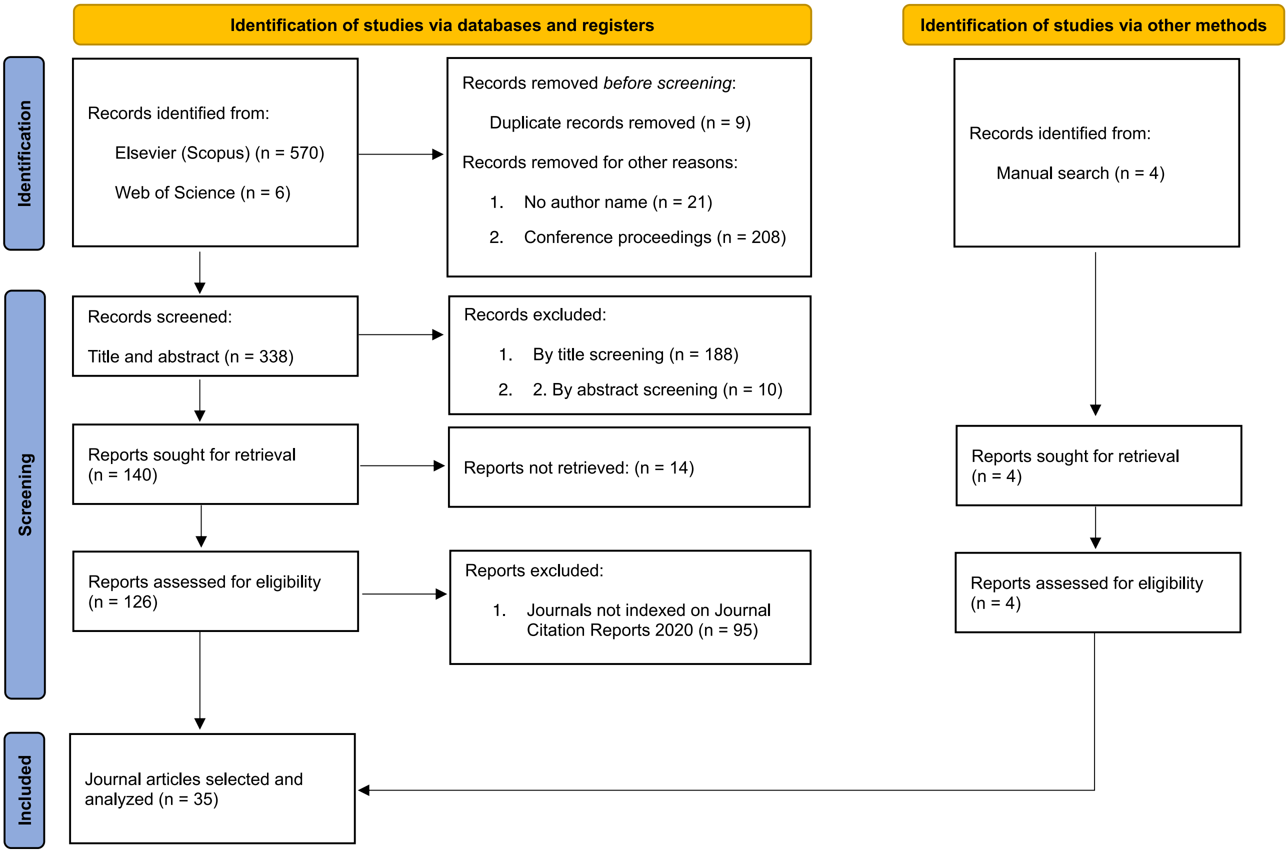

Fig. 10. PRISMA 2020 flow diagram. This summarizes the results obtained from the literature search.

cycle that works with organic fluids instead of water can be a feasible alternative in marine WHRS. Even though the exhaust gas heat coming out of a marine engine can reach the needed temperatures, other waste heat sources as jacket water and lubrication oil lack of such heat quality. By exchanging the working fluid, replacing water for organic fluids like hydrocarbon gasses or hydro chlorofluorocarbons (HCFCs), a steam Rankine cycle is converted to an organic Rankine cycle. The reason behind is that organic fluids present a specific vaporization heat much lower than water (Singh and Pedersen, 2016). This strategy seems attractive but when applied to WHRS onboard vessels it has several limitations. First, a WHRS coupled to a marine engine will be generally installed in the engine room, an enclosed space where operators are constantly working. Because of this, special care about safety needs to be taken. On top of observing the physical properties of the working fluid, toxicity and flammability must be contemplated. Secondly, environmental effects of an accidental release of the working fluid can cause a high impact into the ecosystem, as many organic fluids have very high Global Warming Potential (GWP). Finally, the critical temperature of the working fluid needs to be close to the temperature of the heat source: many organic fluids like cyclohexane have been used in other applications but are not suitable for low-grade heat sources. As in the water T-S diagram, some fluids need a high amount of latent heat to vaporize the working fluid and therefore the efficiency of the heat recovery will not be maximized. Fig. 13 displays an ORC proposal where jacket water cooling from a marine engine is used as heat source.

In this review, the most implemented WHR system was the ORC. A total of 18 journal articles out of the 35 selected, researched about ORC. Yang and Yeh focused on the study of an ORC that recovered waste heat from the jacket water of the marine engine, testing six different organic fluids in order to evaluate which performed most satisfactorily. Out of the six options, they determined the best fluid for the 85 – 95 °C of the jacket water was R600a (Yang and Yeh, 2014). Other authors like Mondejar et al. researched a system working with only one fluid, benzene, implementing the system not only for one propulsion marine diesel engine but for the whole set of engines onboard, composed of four propulsion and four auxiliary engines dedicated to power generation. The exhaust gas of all the engines converged in an ORC where 395.73 kW where recovered, which accounted for approximately 22% of the total power consumption on board (Mondejar et al., 2017). Systems installed on exhaust gas lines can have a negative effect on fuel consumption as they can increase engine backpressure. Following this theory, Baldasso et al. investigated about the design of an ORC system for the recovery of exhaust gas waste heat concluding that the design of units with a minimum pinch point temperature approach could lead to unfeasible designs for the WHR boiler (Baldasso et al., 2020). The combination of other WHR systems with the ORC has been studied in several cases, using mainly supercritical cycles to recover the higher grade waste heat and leaving the ORC for the lower grade (Ouyang et al., 2020d, 2020c; Su et al., 2020). Also used as a complement to more singular technologies like the solid oxide electrolyzer cell (SOEC) dedicated to hydrogen production (Wang et al., 2021) or emission reduction systems like the exhaust gas recirculation system (Lion et al., 2019). Other researchers have explored the use of ORC variations like the dual loop proposed by Civgin and Deniz where exhaust gas, scavenge air and jacket water waste heat was recovered. Authors proposed the recovery of exhaust gas and scavenge air waste heat on the high temperature ORC loop meanwhile jacket water waste heat was recovered on the low temperature ORC loop. Benzene and R245fa organic fluids were selected as high temperature and low temperature working fluids, respectively, yielding 3373 kW of power recovered (Civgin and Deniz, 2021). Another option is the use of only one working fluid but with two different pressures. Liu et al. started from a more conventional WHR system with a steam Rankine coupled with an ORC and from there substituted it for a dual pressure ORC concluding waste heat extraction

Table 5
Final results of PRISMA 2020 search sorted by year of publication.
The table shows the aim of each study, technologies used and temperature range where the proposed system can recover waste heat.

Authors	Aim of the study	Technology used	Temperature range	Year
(Kristiansen and Nielsen, 2010)	Evaluation of the potential of thermoelectric generators to recover waste heat from the exhaust gas, scavenge air, jacket water, lubrication oil of a marine engine as well as from the exhaust gas of an incinerator and the steam excess from a boiler.	Thermoelectric	Medium + Low	2010
(Ma et al., 2012)	Use of combined turbines technology (steam turbine + power turbine) to assess the WHR form the exhaust gas of a two-stroke marine engine.	Power Turbine; Rankine	Medium	2012
(Choi and Kim, 2013)	Analysis of the combination of a trilateral steam cycle paired with an ORC in order to recover waste heat from the exhaust gas of a two-stroke marine engine.	Trilateral; ORC	Medium + Low	2013
(Shu et al., 2013)	Overview of WHR systems that can be applied into two-stroke marine engine and their recovery potential.	Turbine; Absorption and adsorption refrigeration cycles; Thermoelectric; Rankine; ORC, Desalination	Medium + Low	2013
(Larsen et al., 2014)	Analysis of the use of a Kalina process called Split-cycle in order to recover heat from the exhaust gas of a four-stroke marine engine.	Kalina (Split-cycle)	Medium	2014
(Liang et al., 2014)	Combination of a steam Rankine cycle and an absorption refrigeration cycle as WHR system for the exhaust gas of a two-stroke marine engine.	Rankine; Absorption refrigeration	Medium + Low	2014
(Yang and Yeh, 2014)	Optimization of an ORC system for WHR from jacket water of a two-stroke large marine engine.	ORC	Low	2014
(Suárez de la Fuente and Greig, 2015)	Comparison of steam Rankine and ORC working with different fluids in order to recover waste heat contained in the exhaust gas of a two-stroke marine engine. Use of thermal oil as a heat transfer medium to the organic fluids.	Rankine; ORC	Medium + Low	2015
(Singh and Pedersen, 2016)	Review of WHR technologies for maritime applications focusing on the extraction of waste heat from exhaust gas, scavenge air, jacket water of marine engines as well as the exhaust gas of the incinerator.	Rankine; ORC; Supercritical Rankine; Kalina; Turbine; Thermoelectric	High + Medium + Low	2016
(Kyriakidis et al., 2017)	Study of steam Rankine cycles for WHR from the exhaust gas of a marine engine combined with an exhaust gas recirculation system.	Rankine; EGR	Medium + Low	2017
(Mondejar et al., 2017)	Simulation model of an ORC to recover waste heat from the exhaust gas of marine engines. Data logged on board a cruise ship with four-stroke engines.	ORC	Medium + Low	2017
(Mondejar et al., 2018)	Review of the different configurations, studies and types of use of the ORC in order to recover waste heat from the exhaust gas, scavenge air, jacket water and lubrication oil of two and four-stroke marine engines.	ORC (simple, regenerated, double pressure, transcritical and cascade)	Medium + Low	2018
(Lion et al., 2019)	Analysis of WHR possibilities by using an ORC paired with exhaust gas recirculation technology in order to recover the exhaust gas waste heat from a two-stroke marine engine.	ORC; EGR	Medium	2019
(Yuan et al., 2019)	Use of waste heat from the exhaust gas of a four-stroke marine engine to power a combination of absorption refrigeration and freezing	Absorption refrigeration; Freezing desalination	Medium	2019

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Table 5 (*continued*)

Authors	Aim of the study	Technology used	Temperature range	Year
	desalination cycles.			
(Baldasso et al., 2020)	Optimization of an ORC as WHR system to extract heat from the exhaust gas of a two-stroke marine engine, taking in count the backpressure effect.	ORC	Medium	2020
(Feng et al., 2020)	Thermodynamic analysis and performance optimization of the supercritical carbon dioxide Brayton cycle combined with the Kalina cycle for waste heat recovery from a marine low-speed diesel engine	Supercritical CO$_2$ Brayton; Kalina	Medium	2020
(Gude, 2020)	Desalination of ballast water using thermoelectric conversion from waste heat streams like exhaust gas, jacket water, scavenge air and lubrication oil of marine engines along with other sources like incinerator flue gas and excess of steam on boilers.	Thermoelectric	Medium + Low	2020
(Lion et al., 2020)	Overview of Rankine based WHR systems like steam and ORC. Assessment of the combination of different emission reduction technologies with WHR systems and its impact.	Rankine; ORC	Medium + Low	2020
(Liu et al., 2020a)	Combination of steam and organic Rankine cycles using waste heat from exhaust gasses and jacket water of a two-stroke marine engine	Rankine; ORC	Medium + Low	2020
(Liu et al., 2020b)	Recovery of waste heat from exhaust gas and jacket water of a two-stroke marine engine by means of a steam Rankine, an ORC and an absorption refrigeration cycles.	Rankine; ORC; Absorption refrigeration	Medium + Low	2020
(Ouyang et al., 2020b)	Design of a WHR system for exhaust gas heat recuperation from a four-stroke natural gas marine engine along with a cold energy absorption system aimed to extract spare cold energy from the LNG supply to the engine.	Supercritical Brayton; Absorption refrigeration; Organic flash; Liquefied-air energy storage and Sewage purification	Medium + Low + Cold	2020
(Ouyang et al., 2020a)	Design of a WHR system with ORC, desalination and absorption refrigeration cycles in order to recover energy from exhaust gas, jacket water, scavenge air and lubrication oil from a two-stroke marine engine.	ORC; Desalination; Adsorption refrigeration	Medium + Low	2020
(Ouyang et al., 2020c)	Evaluation of a combined WHR system in order to maximize the energy recovery from the exhaust gas of a four-stroke dual-fuel marine engine.	Supercritical CO$_2$ Brayton; ORC; Absorption refrigeration and Capillary desalination	Medium + Low	2020
(Ouyang et al., 2020d)	WHR from the exhaust gas of a four-stroke dual-fuel marine engine by means of a supercritical Brayton and Absorption cycles. Further reuse of latent heat with organic Flash, Rankine and Trilateral cycles.	Supercritical Brayton; ORC; Organic Flash Cycle; Organic Trilateral Cycle; Absorption refrigeration	Medium + Low	2020
(Su et al., 2020)	Utilization of exhaust gas waste heat from a four-stroke marine dual-fuel engine to power Rankine and ORC turbines. Use of spare cold energy from LNG supplied to the engine for freezing desalination of sea water.	Supercritical CO$_2$ Rankine; ORC; Freezing desalination	Medium + Low + Cold	2020
(Zhu et al., 2020)	Review of main thermodynamic cycles as WHR systems for the waste heat of exhaust gas, scavenge air, jacket water and lubrication oil of marine engines. Further analysis of their integration with emission reduction technologies.	Rankine; ORC, Kalina; CO2-based power cycles	Medium + Low	2020

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Table 5 (*continued*)

Authors	Aim of the study	Technology used	Temperature range	Year
(Civgin and Deniz, 2021)	Analyzes WHR by applying a dual-loop ORC to extract heat from exhaust gas, jacket water and scavenge air of a two-stroke marine engine.	ORC	Low	2021
(Lebedevas and Čepaitis, 2021)	Implementation of an ORC on a four-stroke marine engine in order to recover waste heat from the exhaust gas.	ORC	Medium	2021
(Ouyang et al., 2021a)	Implementation of a dual pressure ORC as WHR system from exhaust gas, jacket water and scavenge air of a two-stroke marine engine.	ORC	Medium + Low	2021
(Qu et al., 2021)	WHR system analysis of an installation of power, steam and ORC turbines to recover heat from the exhaust gas of a two-stroke marine engine.	Power Turbine; Rankine; ORC	Medium + Low	2021
(Sakalis, 2021)	Potential of supercritical CO_2 cycles to recover waste heat from the exhaust gas, jacket water and scavenge air from a two-stroke marine engine.	Supercritical CO_2	Medium + Low	2021
(Wang et al., 2021)	Integration of a solid oxide electrolyzer cell as a WHR system dedicated to hydrogen production. Combination with an ORC cycle in order to extract heat from exhaust gas, jacket water and scavenge air of a two-stroke marine engine.	SOEC; ORC	Medium + Low	2021
(Wang et al., 2022b)	Assessment of four different supercritical CO_2 cycles combined with an absorption refrigeration system for the recovery of waste heat contained in the exhaust gas of a two-stroke marine engine.	Supercritical CO_2; Absorption refrigeration	Medium	2022
(Wang et al., 2022a)	Use of exhaust gas waste heat from a diesel engine in a supercritical CO_2 power cycle.	Supercritical CO_2 Brayton	Medium	2022

Table 6

Final results of PRISMA 2020 search sorted by year of publication. The table shows the heat source used, type of study, and efficiency attained.

Authors	Heat source	Type of study	Conclusions
(Kristiansen and Nielsen, 2010)	Exhaust gas, scavenge air, jacket water and lubrication oil of a marine engine as well as from the exhaust gas of an incinerator and the steam excess from a boiler.	Case study with data extracted from the bulk carrier M/V Rosita.	Identification of main waste heat sources on the vessel: exhaust gas from main and auxiliary engines and boilers, scavenge air, jacket water and lubrication oil.
(Ma et al., 2012)	Exhaust gas.	Thermodynamic analysis with data of a MAN 9K98ME-C7 engine database from China State Shipbuilding Corporation.	The thermal efficiency of the engine is increased from 50.6% (standalone) to 53.8% (with WHR system).
(Choi and Kim, 2013)	Exhaust gas.	Case study with data extracted from the technical file for HYUNDAI-MAN B&W 12K98MC—C Mk6 of the containership M/V Hyundai Jakarta (6800 TEU).	WHR system application to the power system increased efficiency 2.824%.
(Larsen et al., 2014)	Exhaust gas.	MATLAB simulation, using Aspen Plus for verification and NIST REFPROP 9.0 with data extracted from (Bombarda et al., 2010)	Reheat leads to 3.4% higher power output for the reference cycle and 5.1% for the SC process. Split-cycle process with reheat produced 11.4% more power for the same heat source conditions.
(Liang et al., 2014)	Exhaust gas.	Computer simulation with data extracted from Sulzer RTA 96C engine manual.	Higher exergy efficiency can be achieved while recovering the energy of expanded steam at turbine outlet to generate cooling energy. With ideal conditions, exergy efficiency is increased by 84%
(Yang and Yeh, 2014)	Jacket water.	FORTRAN simulation, using NIST REFPROP 9.0 with data extracted from Wärtsilä RT-flex96-B Marine Installation Manual.	Concludes an ORC with R600a is the best performer of the fluids studied.
(Suárez de la Fuente and Greig, 2015)	Exhaust gas.	MATLAB simulation, using NIST REFPROP 9.0 for the working fluids and CoolProp for the thermal oil.	Designed ORC can achieve 16.7% over water-based Rankine cycle.
(Kyriakidis et al., 2017)	Exhaust gas.	MATLAB simulation, using NIST REFPROP 9.0 based on the typical data of a large two-stroke marine diesel engine.	Steam Rankine cycles with three-pressure level configuration produces more power than the configuration than two-pressure levels. Three-pressure level configuration is more suitable for ships that operate in both Tier II and Tier III.
(Mondejar et al., 2017)	Exhaust gas.	Experimental temperature data logged during vessel	Average net power production of the ORC represented

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Table 6 (*continued*)

Authors	Heat source	Type of study	Conclusions
		operation. IPSEpro system model and MATLAB simulation, using NIST REFPROP 9.1.	approximately 22% of the total power consumption on board.
(Lion et al., 2019)	Exhaust gas.	Ricardo WAVE engine model validated against experimental data. Engineering Equation Solver (EES) simulation and database for ORC.	Fuel economy benefit of 5.4% in Tier II and 5.9% in Tier III engines.
(Yuan et al., 2019)	Exhaust gas.	Computer simulation coupled with experimental data.	Having an ammonia–water rich solution, COP of the system can be increased from 10 to 16%.
(Baldasso et al., 2020)	Exhaust gas.	MATLAB simulation, using engine performance maps.	Reduction of 5.6 - 6.3% of the engine specific fuel consumption.
(Feng et al., 2020)	Exhaust gas.	MATLAB simulation, using NIST REFPROP 9.0 and data extracted from MAN B&W 8S90ME-C10.2 engine manual.	Proposed system reduced average annual fuel consumption in auxiliary engines by 16.62% and EEDI 15.01%.
(Gude, 2020)	Exhaust gas, jacket water, scavenge air and lubrication oil of marine engines along with other sources like incinerator flue gas and excess of steam on boilers.	Case study with data extracted from the M/V Rosita (Kristiansen and Nielsen, 2010).	Power recovery of approximately 133 kW of electricity by using the heat differences between the ambient seawater and the proposed waste heat streams.
(Liu et al., 2020a)	Exhaust gasses and jacket water.	MATLAB simulation, using data extracted from the MAN B&WK98ME C7.1-TII manual.	WHR system designed in this work improves over 60% and 27% the thermal efficiency of the engine in comparison with SSRC and DPORC respectively.
(Liu et al., 2020b)	Exhaust gas and jacket water.	MATLAB simulation, using NIST REFPROP 9.1 and data extracted from MAN B&W 14K98ME-C7.1-TII project guide.	The designed WHR system extracts 7938 kW output power and 2940 kW of cooling capacity when the engine runs at 100% MCR.
(Ouyang et al., 2020b)	Exhaust gas. Cold energy from LNG supply.	MATLAB simulation, using NIST REFPROP.	Increase of 5.14% in system thermal efficiency
(Ouyang et al., 2020a)	Exhaust gas, jacket water, charge air and lubrication oil.	MATLAB simulation, using NIST REFPROP and data extracted from Wärtsilä RT-flex96C.	Increase of 1.45% of overall system efficiency recovering 44.13% of engine waste heat.
(Ouyang et al., 2020c)	Exhaust gas.	Numerical simulation, using NIST REFPROP and experimental data from a Guanxi Yuchai Machinery dual-fuel engine.	Exergy efficiency increased in 0.89%
(Ouyang et al., 2020d)	Exhaust gas.	MATLAB simulation, using NIST REFPROP and experimental data from a Guanxi Yuchai Machinery dual-fuel engine.	First thermodynamic law efficiency was increased by 4.66% after installing the WHR system.
(Su et al., 2020)	Exhaust gas. Cold energy from LNG supply.	Numerical simulation, using NIST REFPROP and experimental data from two YC6C dual-fuel engines.	EEOI is reduced in 5.05 gCO_2 / tonne·nm with the installation of the proposed WHR system.
(Civgin and Deniz, 2021)	Exhaust gas, jacket water and scavenge air.	Thermodynamic analysis with data taken from Ship Engine Room Simulator from Kongsberg.	Best and safest result (avoiding benzene) reached 3126 kW of calculated net power.
(Lebedevas and Čepaitis, 2021)	Exhaust gas.	Thermoflow simulation, using data from a 4-stroke, 460 mm bore, 12 cylinders marine engine.	With the proposed WHR system, power plant COP increased by 6.2% meanwhile plant efficiency increased 5.3%.
(Ouyang et al., 2021a)	Exhaust gas, jacket water and scavenge air.	MATLAB simulation, using NIST REFPROP 9.1 and data extracted from MAN 6S40ME-C9.5 CAES – engine room dimensioning.	Under the estimated temperatures and pressures that maximize exergy efficiency, this is 60.24%
(Qu et al., 2021)	Exhaust gas.	Thermodynamic analysis, using Excel software and NIST REFPROP 9.1 with data provided by a 6S50ME-C8.2 case study diesel engine.	With engine operation condition of 100% MCR, the total power generation reached by the WHR system was 1079.1 kW.
(Sakalis, 2021)	Exhaust gas, jacket water and scavenge air.	Numerical simulation with data extracted from MAN B&W S60ME-C10.5-TII Project guide.	WHR system proposed can increase energy conversion efficiency of the main engine by 6.6 - 7.25%, compared to standalone diesel operation.
(Wang et al., 2021)	Exhaust gas, jacket water and scavenge air.	MATLAB simulation, using NIST REFPROP with data extracted from Wärtsilä RT-flex96C marine diesel engine. SOEC data extracted from (AlZahrani and Dincer, 2016; Mohammadi and Mehrpooya, 2018; Zhang et al., 2013).	Integration system with H_2 production achieves 53.56% efficiency. Increase of 1.45% of overall system efficiency and 44.13% of engine waste heat recovered.
(Wang et al., 2022b)	Exhaust gas.	MATLAB simulation, using NIST REFPROP 9.1 and data extracted from MAN 8S90ME-C10.2 (Tian et al., 2017).	After the multi-objective optimization, product exergoenvironmental impact is decreased by 12.83%.
(Wang et al., 2022a)	Exhaust gas.	MATLAB simulation, using NIST REFPROP 10.0.	Thermal and exergy efficiency reached 33.17 and 61.93%, respectively.

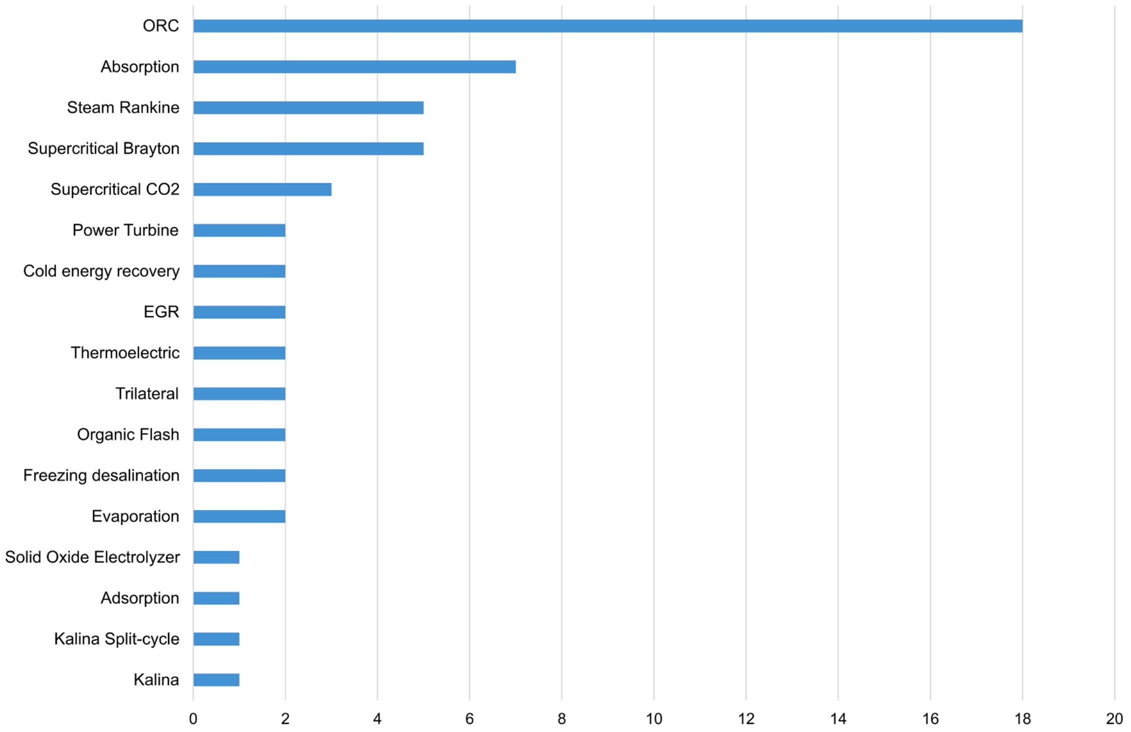


Fig. 11. PRISMA bar chart. The quantity of relevant papers for each WHR technology found in the literature search is shown.

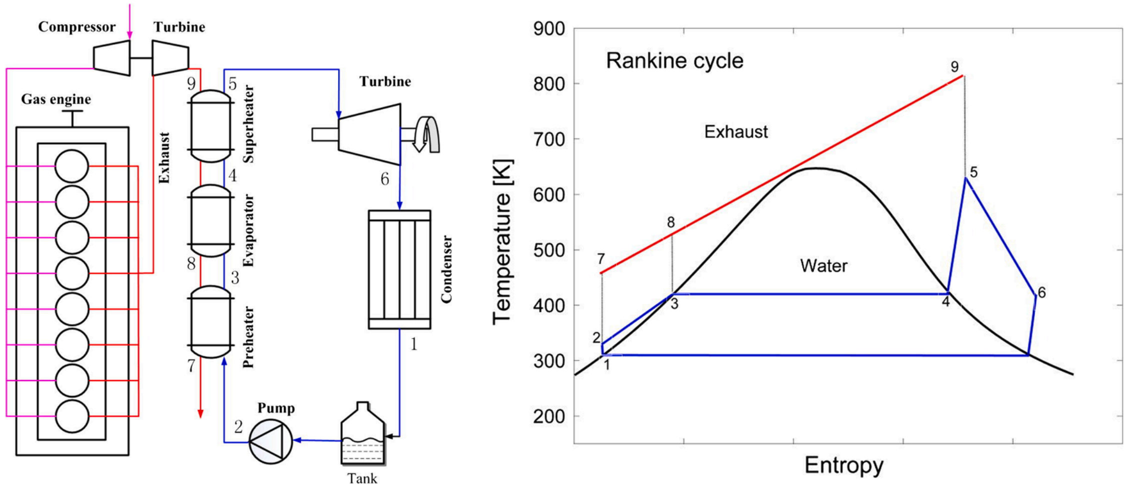


Fig. 12. Schematics and T-S diagram of a marine steam Rankine cycle recovering waste heat from the exhaust gas current (Shu et al., 2016).

from exhaust gas and jacket water of a marine engine became more efficient when using the dual pressure ORC instead of the steam Rankine plus a simple ORC (Liu et al., 2020a).

Supercritical Rankine

This is a variation of the conventional Rankine cycle with its maximum working pressure over the critical point. The working fluid enters the boiler as liquid or subcooled liquid at a pressure higher than its critical pressure and it is heated, bypassing the two-phase region and resulting in a lower destruction of exergy (Chen et al., 2011). This strategy allows supercritical cycles to achieve a higher efficiency, compared to subcritical ones. Since organic fluids have a lower critical temperature than water, supercritical organic Rankine cycles are more convenient for low-grade heat recovery. An off-design control can be implemented so, by varying the speed of the pump, the same device can operate at either supercritical or subcritical state and adapt to the heat source and mass flow rate (Astolfi, 2017). On the contrary, the application of higher pressures involves the use of more powerful machinery. In many cases, multistage centrifugal pumps are used to achieve higher pressures, which can have a relevant energy consumption. Also, heat exchangers would need to be modified from conventional cycles. In Fig. 14, a T-S diagram of a supercritical organic Rankine cycle is shown.

Su et al. presented a system where a supercritical Rankine cycle with CO_2 as working fluid was the head of its WHR proposal. The system focused on the recovery of waste heat from the exhaust gas of a dual-fuel engine where the supercritical Rankine cycle worked with an ORC and a cold energy recovery system for carbon liquefaction and later capture. Their proposal greatly affected the energy efficiency operational indicator (EEOI), reducing it from 28.41 to 23.36 gCO_2/ton·nm (Su et al., 2020).

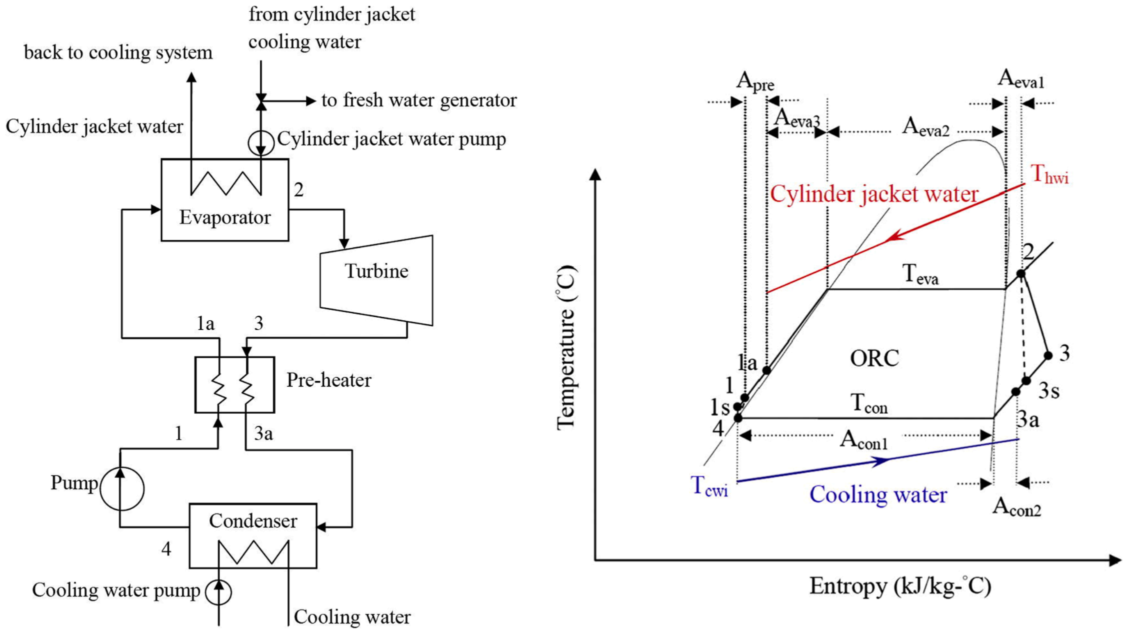


Fig. 13. Schematics and T-S diagram of an organic Rankine cycle proposed to use in a marine engine (Yang and Yeh, 2014).

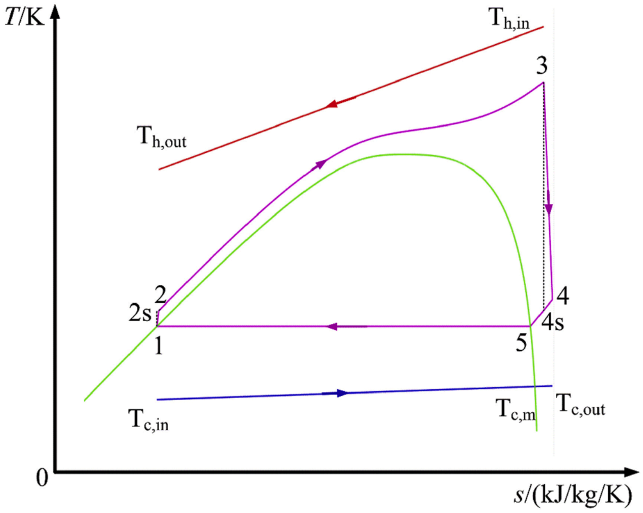


Fig. 14. Temperature-entropy diagram of a supercritical Rankine cycle (Yang et al., 2023).

Brayton cycle

Also referred to as Joule cycle, the Brayton cycle starts with a compressor where the selected working gas is pressurized and later, in a heat exchanger, efficiently heated by a high-temperature heat source at a constant pressure. Finally, the gas is expanded in a turbine where it produces mechanical work. Brayton cycles usually have lower investment costs than other cycles (Meana-Fernández et al., 2022).

As in Rankine cycles, the turbine of Brayton cycles is usually coupled to an electric generator (Beér, 2004). The main difference with a Rankine cycle, is that a Brayton cycle operates with a single-fluid phase. This avoids quality issues present in the Rankine cycle after expansion. Also in comparison with Rankine cycles, Brayton cycles' turbomachinery is smaller. The air-standard Brayton cycle is optimized for high-grade heat sources, which are not very common in marine engines. For a better thermal matching with the waste heat source, Brayton cycles can be optimized by varying the working fluid. The use of organic fluids, either in its pure form or in mixtures, generally improves the efficiency of the cycle as their vaporization temperatures are usually lower (Dutta et al., 2014). In conventional Brayton cycles, the materials used need to endure very high temperatures so the use of organic fluids with lower heat sources also allows to use simpler materials or higher pressure ratios.

Supercritical Brayton

Similarly to supercritical Rankine cycles, on supercritical Brayton cycles a mass of gas circulates over the critical pressure point. Usually, gasses with low critical temperature and pressure characteristics are used. Despite the improvement of the supercritical cycle, low temperature heat sources are not really recovered by using this technique. Ouyang et al. published two articles where the head of the WHR system was a supercritical Brayton. In their first paper, a regenerative supercritical Brayton cycle recovered waste heat from the exhaust gas of a dual-fuel marine engine, followed by a cascade system comprised of an organic flash cycle and an absorption refrigeration cycle. From several organic fluids as CO_2, propylene, pentane, cyclohexane and others, the authors selected CO_2 as the working fluid due to its stability and thermodynamic performance under high pressure conditions. The supercritical CO_2 Brayton cycle had to be coupled with and organic flash and an absorption refrigeration cycles in order to extract the remaining waste heat contained on the exhaust gas that the Brayton cycle could not recover as the temperature of the exhaust gas at the inlet of the organic flash cycle was estimated to be 200 °C. The supercritical Brayton cycle proposed, in combination with the rest of the WHR system, increased thermal efficiency of the engine 5.14% (Ouyang et al., 2020b). In comparison with an air-standard Brayton cycle, supercritical CO_2 Brayton cycles result an attractive solution for the use onboard vessels as they achieve higher efficiency at low temperatures, need less compression work, and due to the high density of the working fluid, use smaller turbomachinery. On the contrary, in terms of safety, the use of CO_2 in machinery placed in enclosed spaces presents some degree of risk as it displaces oxygen.

In a following article, Ouyang et al. explored the performance differences of a supercritical Brayton cycle when paired with an ORC, an organic flash and an organic trilateral cycles. In this case, the working medium for the supercritical Brayton cycle was selected from a set of zeotropic-mixtures formed by CO_2 and other pure working-fluids being the most efficient R32-CO_2 (Ouyang et al., 2021b). Previously, Dutta et al. tested different organic fluids on Brayton cycles and concluded that R32 was one of the best performers (Dutta et al., 2014). In Ouyang et al. experiment, all Rankine derived cycles used R245fa. Out of the three options presented, results indicated that the combination of the supercritical Brayton cycle with the ORC was more competitive than flash an trilateral cycles, all being evaluated under the same conditions (Ouyang et al., 2020d). Some other publications did not experiment with different organic fluids but directly proposed a supercritical Brayton cycle with CO_2 as working fluid. Wang et al. presented a recuperative supercritical CO_2 Brayton cycle that recovered waste heat from the exhaust gas and concluded that, in order to maximize WHR, some extra systems should be applied to the downstream of the exhaust gas and to the expanded CO_2 after the Brayton turbine. In this paper, one of the major advantages of applying a supercritical CO_2 Brayton cycle is the possibility of working with high-grade heat as the exhaust gas of the proposed engine had 633.1 °C but on the other hand, the temperature of the exhaust gas after passing the supercritical Brayton cycle was still 276.59 °C, which is considered medium-grade quality heat (Wang et al., 2022a). If this temperature is not common for the exhaust gas of low speed engines and not usual either on medium speed engines, there are high speed marine engines that can reach very high exhaust gas temperatures (Rolls Royce and MTU Solutions, 2021). Fig. 15 reproduces the proposal made by Wang et al.

Alternatively, Feng et al. combined a supercritical CO_2 Brayton cycle with a Kalina cycle in order to recover the overall waste energy from the exhaust gas of a two-stroke marine engine with a reduction in the average annual fuel consumption of 16.62% (Feng et al., 2020).

Kalina cycle

The Kalina cycle is a relatively new thermodynamic cycle, proposed by Alexander Kalina (Kalina, 1983). Its advantage falls in its capability to recover low temperature heat, which makes it very suitable for marine diesel engines and their WHR systems (Dincer and Demir, 2018). In general terms, a Kalina cycle can be described as a modified Rankine cycle where a mixture of water and ammonia is used as working fluid. This feature allows to increase the temperature at which thermal energy is absorbed but also to decrease the temperature at which it is released, increasing the thermal efficiency in comparison with a conventional Rankine cycle (Meana-Fernández et al., 2022). Kalina cycles are also more flexible than conventional Rankine cycles. Since the mass fraction of the ammonia can be varied as needed, thermal match with the heat source becomes easier. The layout of this proposal is displayed in Fig. 16.

With the advantage of being capable of the recovery of low-grade heat, Feng et al. placed a Kalina cycle at the downstream of a supercritical CO_2 Brayton cycle. In this case, the Kalina cycle was in its conventional manner, with an ammonia-water mixture as the working fluid and performance of the cycle was assessed with the variation of the expander inlet pressure at different ammonia mass concentrations, from 30 to 80% NH_3. The single-objective optimization for the Kalina cycle concluded that both maximum net power output and efficiency were with an expander inlet pressure of 3 MPa and a mass concentration of 30% NH_3, yielding 1914.3 kW and 48.1%, respectively. When coupled with the supercritical CO_2 Brayton cycle, the multi-objective optimization determined that best results were obtained when NH_3 concentration remained at 30% but the Kalina expander inlet pressure was reduced to 2 MPa. On the overall WHR system, the Kalina net power output and efficiency resulted in 1733.5 kW and 43.5%, respectively (Feng et al., 2020).

Kalina split-cycle

This cycle is based on the conventional Kalina cycle but with some major differences. First, two different water-ammonia mixtures with different mass concentration are used. The mixture with higher ammonia concentration would evaporate completely meanwhile the leaner mixture will be heated only to the bubble point state. This is done in order to get lower temperatures on the process going from liquid to vapor. The evaporation temperature curve can be somehow adjusted to the heat source by modifying the mass fraction of the mixtures (Larsen et al., 2014; Nguyen et al., 2014). In Fig. 17 the T-S diagram used by Larsen et al. is presented. In the figure, the dashed lines between T_b and 2_a represent the temperature-entropy area where the mixture can vary due to the modification of the stream concentration used.

This is a highly specific process and on the analyzed literature only one publication researched about this technique. Larsen et al. proposed a WHR system for the exhaust gas of marine engines based on a Kalina Split-cycle. Results indicated an increase of 5.1% of power output due to the higher boiler temperature and lower expansion pressure but with the disadvantage of a more complex layout (Larsen et al., 2014). When designing WHR machinery to implement onboard vessels the complexity of the system needs to be observed as engine rooms are already tight in space and complex systems will place a higher workload in crews. Also, more complex systems may require longer payback periods. In general terms, authors have presented several modifications of the Kalina cycle in the literature as the Kalina-split or the preheat of the mixture before the main heat exchanger, but it has been difficult to find techniques that improve the efficiency of the original Kalina cycle (Valdimarsson, 2003).

Refrigeration cycles

Main thermodynamic cycles extract the majority of the high and medium quality waste heat but usually, at the outlet of these cycles, there is still waste heat of a lower quality that should be recovered in order to maximize recovery. Refrigeration cycles generally use low temperature heat sources in order to generate cold energy, which is

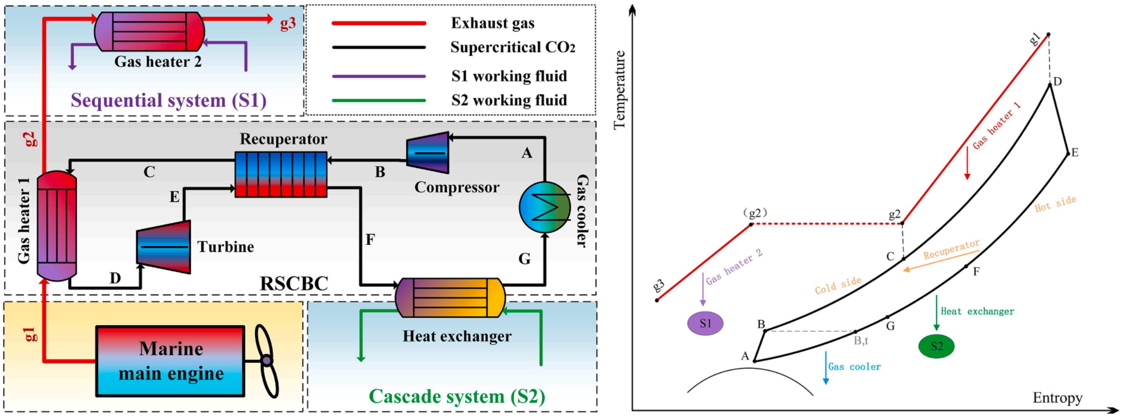


Fig. 15. Layout and T-S diagram of the supercritical CO_2 Brayton cycle proposed by Wang et al. (Wang et al., 2022a).

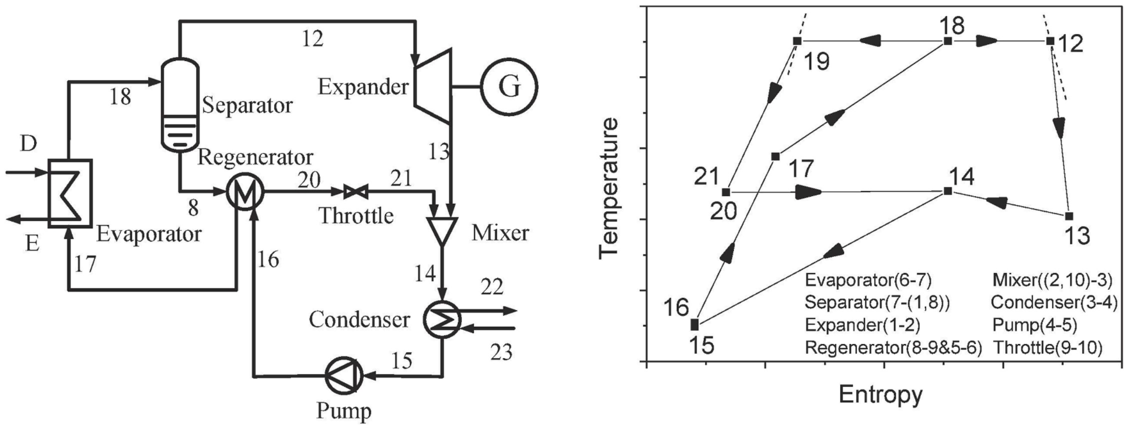


Fig. 16. Schematics and T-S diagram of the Kalina Cycle proposed by Feng et al. (Feng et al., 2020).

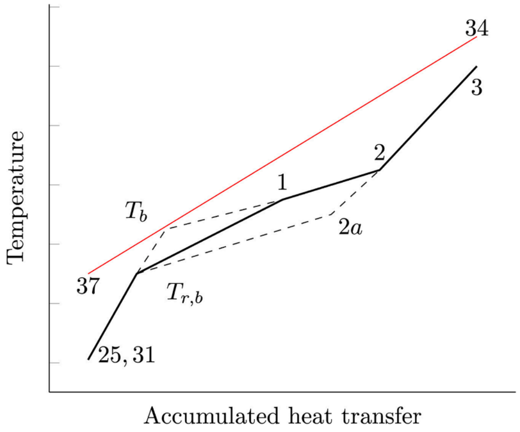


Fig. 17. T-S diagram of the Kalina-split cycle proposed by Larsen et al. (Larsen et al., 2014).

demanded onboard for air conditioning and cold storage of medical products and food. Conventional refrigeration systems installed onboard, based in mechanical compression, are less efficient and consume fuel while the following reviewed sorption refrigeration systems extract the needed energy from waste heat, are almost noise-free and require very low maintenance (Shu et al., 2013). These systems are usually coupled with other thermodynamic cycles like Rankine, ORC or Brayton.

Absorption

The absorption refrigeration system is able to produce cold from a heat source. This is a vapor refrigeration technology based on dissolving the working fluid, which is typically formed of two fluids: ammonia and a carrier liquid, usually water. Alternatively, the use of water as refrigerant and lithium bromide as absorbent is also in use. Each one of these two fluids act as refrigerant and absorbent, respectively. The mixture of fluids in liquid phase will be pressurized by a pump. The main advantage over the compression refrigeration falls into the work supplied to the system: a liquid can be more efficiently pumped than a gas can be compressed. Once the high-pressure mixture of refrigerant and absorbent reaches the generator, which is basically a WHR system working as a heat exchanger, it boils off taking the heat from the waste heat source. This separates refrigerant and absorbent. Later, the refrigerant uptakes heat during the evaporation process, cooling the environment. This technology has been adopted by several authors in order to specifically recover low temperature waste heat either as a downstream extracting method after another WHR device or to recover waste heat from low-grade heat sources as lubrication oil. Fig. 18 shows a double effect absorption refrigeration cycle proposed by Zhao et al. to recover waste heat in ocean-going vessels (Zhao et al., 2021).

As a part of a larger, integrated WHR system Ouyang proposed to include an absorption refrigeration cycle downstream of a supercritical Brayton cycle and an organic flash cycle. In this way, the lowest grade waste heat of the marine engine exhaust gas could be recovered. With this configuration a maximum cooling capacity of 163.65 kW was obtained (Ouyang et al., 2020b). In a later publication, the same authors

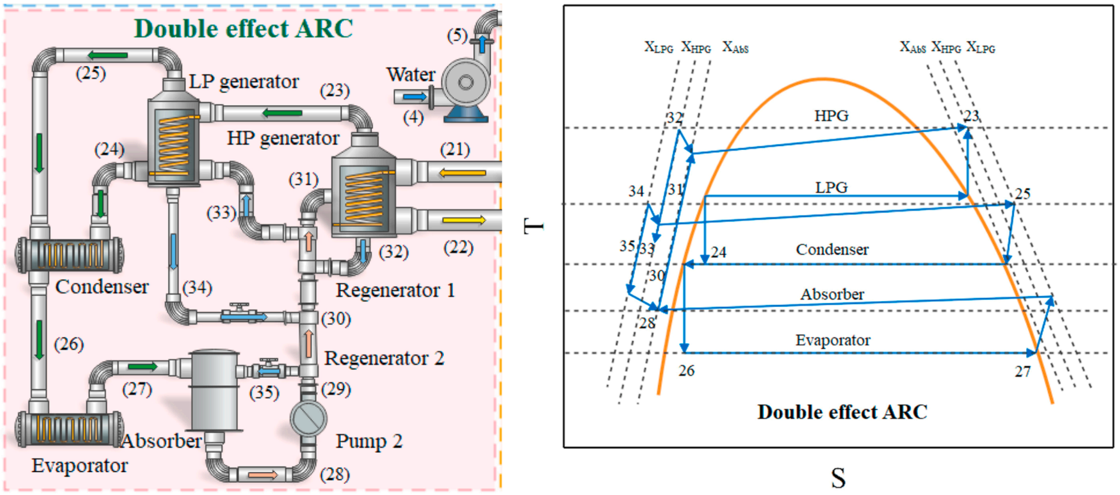


Fig. 18. Double effect absorption refrigeration cycle and its T-S diagram. Adapted from (Zhao et al., 2021).

replaced the organic flash cycle for an ORC system and included a desalination system downstream of the absorption refrigeration cycle. In this study, tested in a very similar engine (1558.76 kW for the first article and 1498.22 kW in the later one, both at 100% load) maximum cooling capacity of the absorption cycle resulted in 94.3 kW (Ouyang et al., 2020c). With the same philosophy, Liu et al. proposed a WHR system with a steam Rankine fed by jacket cooling water and recovering waste heat from the exhaust gas line with an ORC downstream. In this case, the waste heat for the absorption refrigeration cycle came from the jacket cooling water after being vaporized and expanded on the steam Rankine cycle. This configuration was applied to a two-stroke marine engine with 84,280 kW of shaft power and a cooling capacity of 2940 kW was obtained (Liu et al., 2020b). As an average, the application of this cycle can obtain a cooling capacity of 6.7% of engine shaft power. In order to directly recover waste heat from the exhaust of a marine engine, Yuan et al. presented an absorption refrigeration cycle where exhaust gas directly entered the generator of the absorption cycle. With the aim of maximizing energy recovery, a freezing desalination system was placed following the absorption cycle. Sea water was frozen by the vaporization of ammonia in two evaporators. The whole system had a cold storage cooling capacity of 5.2 kW meanwhile the pre-desalination branch capacity reached 4.7 kW (Yuan et al., 2019). Absorption refrigeration systems are interesting to recover waste heat but, in comparison with vapor compression refrigeration systems, the first are usually larger and more complex, requiring additional space.

Adsorption

Very similar to the absorption refrigeration cycle, the major difference falls in how the refrigerant fluid behaves: in an absorption cycle the refrigerant vapor is absorbed into a liquid meanwhile in an adsorption cycle the refrigerant vapor is adsorbed into a solid (Rupam et al., 2020). Substances used as solid adsorbent can be hydrophilic, with special affinity towards polar substances like water, or hydrophobic, when they have affinity for oils. The adsorbate, in liquid form, is in charge of creating the cooling effect. If compared with an absorption system, adsorption technology is simpler and therefore more reliable (Liu and Leong, 2005). In Fig. 19, the concept of adsorption cooling cycle is represented by a circuit and a T-S diagram.

Adsorption cycle is also generally adopted when low temperature waste heat is present (Teng et al., 1997). A less applied technology in the field of WHR from marine engines, Ouyang et al. presented a system dedicated to recover waste heat from lubrication oil from a MAN6S40ME-C9.5 two-stroke engine with a full load shaft power of 6810 kW that equipped an adsorption refrigeration cycle. This is relevant due the very low temperature of the heat source in comparison with others like exhaust gas and scavenge air. In this study, Ouyang et al. selected a two-bed regenerative adsorption device that achieves high cooling coefficient of performance (COP) and, by configuring the beds to work alternatively, achieved continuous refrigeration. At the common used load of the engine (70% MCR) this refrigeration cycle was able to reach a cooling capacity of 88 kW (Ouyang et al., 2020a).

While absorption refrigeration cycles have a slightly higher COP, adsorption systems present some advantages that make them suitable for the use onboard vessels. Adsorption refrigeration does not need corrosion protection while absorption systems working with ammonia do. Because of that, life expectancy of adsorption systems is higher.

A major drawback of all refrigeration systems proposed in the reviewed literature and based in processes that use waste heat to operate, is their high dependance to the heat source. If the heat source is inconsistent, the efficiency and cooling capacity of the system may be compromised. As with other waste heat recovery systems shown, careful consideration of the operative of the vessel needs to be done prior to the installation of these technologies.

Desalination

When operating, ships require large amounts of freshwater in order to satisfy the demand of the crew and the machinery, like steam generation. Desalination process consists mainly in the removal of total dissolved solids (TDS) from a water source. In general terms, desalination is applied to sea water in order to obtain fresh water. Depending on the technology used, the grade of desalination will be different, and the obtained product may have a different application. Desalinated water from an evaporation process usually has very little content of TDS, maintaining salinity around 2 parts per million (ppm), while membrane reverse osmosis (RO) process keeps salinity below 2000 ppm (Alfa Laval, 2020; Guler et al., 2015). Consequently, fresh water from an evaporator is more prone to be used as technical water for industrial processes and the product of a RO unit might be better for human consumption. After filtration, chlorination or any other disinfection processes like ultra-violet light exposure, fresh water from desalination can be considered drinkable water (Mulić and Jerončić Tomić, 2020).

Flash evaporation

One of the most well-known techniques to recover waste heat from marine engines is the distillation of sea water by flash evaporation. Historically, jacket water has been used as the main heat source for water generators on board ships. This was achieved creating a vacuum inside a chamber and forcing the water to flash at lower temperatures (Zhang et al., 2017). Flashed steam is later cooled down and condensed

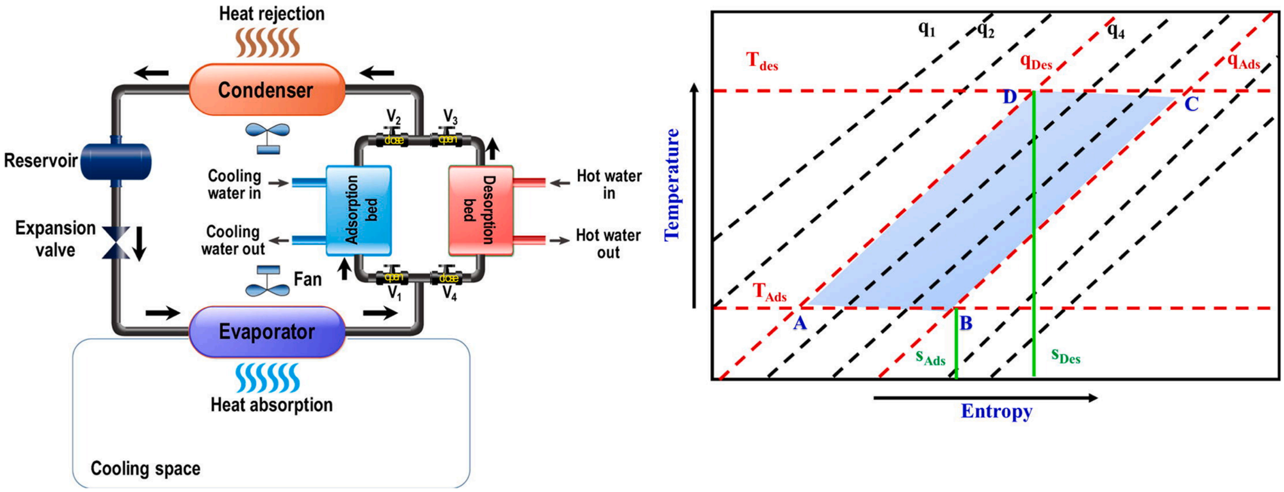


Fig. 19. Adsorption refrigeration cycle proposed by Rupam et al. along with its T-S diagram (Rupam et al., 2020).

by seawater. This can be done in one or multiple stages. Multistage flash desalination takes unflashed brine from the first stage and uses its thermal energy to produce desalination in a second stage, avoiding the need of adding more heat. This general idea was modified by Ouyang et al. in order to extract the lowest grade heat on a cascade WHR system with the pumping of the seawater done by capillary force so no extra work is applied (Ouyang et al., 2020c). The same concept was applied when a dual-pressure ORC system was proposed, placing a single stage flash evaporator at the outlet of the ORC in order to maximize the recovery of waste heat from the exhaust gas of the marine engine. The authors concluded that a freshwater production of 146 kg/h could be achieved when the engine load was at 70% MCR (Ouyang et al., 2020a).

In comparison with other systems reviewed in this article, like refrigeration technologies, desalination of sea water through flash evaporation always needs an extra addition of energy. In order to use low-grade waste heat to flash water, the pressure of the chamber must decrease so a vacuum system, like a venturi, needs to be implemented. Besides, water production by this method produces brine and eventually scaling so operators need to take care of the device to avoid a decrease in its performance. If water production is a priority, flash evaporation can be a solution to satisfy the needs onboard and recover waste heat but when designing a WHRS other systems might achieve higher results.

Freezing desalination

Another way to utilize the lowest grade waste heat that other thermodynamic cycles are not able to extract is the freezing desalination. This process works producing ice crystals that exclude concentrated saltwater, brine, during its formation. Freshwater is obtained from the separation of the ice crystals and later melting. A great advantage of the freezing desalination process over the evaporative distillation is that the energy required is only a seventh part of what the evaporation process needs (Najim, 2022). Also, the technology has minimal potential corrosion and very little scaling, in comparison with other desalination techniques. On the other hand, the ice and brine mixture is more difficult to handle and process. Yuan et al. proposed a system with a two-stage freezing desalination system that used ammonia from a prior absorption desalination system in an ammonia-sea water heat exchanger that produced fresh water at a rate of 20–22 L/h (Yuan et al., 2019). In case the marine engine installed on the vessel is of a dual-fuel type and a supply of LNG is available, freezing desalination can be implemented as a cold energy recovery system from the vaporization of LNG. Su et al. used this principle to complement a WHR system consisting of a supercritical CO_2 cycle and a subcritical ORC in order to enhance the overall efficiency of the proposal (Su et al., 2020). In Fig. 20 the proposal of Ni et al. where waste heat is recovered from the exhaust gas of a marine engine in order to feed an absorption refrigeration cycle coupled with a two-stage crystallization subsystem.

Reverse osmosis

The desalination process based on membrane reverse osmosis produces freshwater by overcoming the osmotic pressure of the seawater. When pressure is applied to the saltwater feed, freshwater flows across the osmotic membranes, leaving behind the salts. This technology does not need heating or phase separation but uses a high amount of energy in the pressurization of the saltwater. Because of this, reverse osmosis is not a proper WHR system but a device where the recovered energy, in the form of electric power, can be utilized. The amount of energy used for reverse osmosis desalination varies with the temperature of the feed as higher pressures need to be applied when seawater gets colder.

On its study of thermoelectric waste energy harvesting from the various main engine waste heat sources, Gude integrated a RO unit powered by the electricity recovered by thermoelectric generators. With the power recovered and assuming a feed water temperature of 25 °C, 21.3 m^3 of freshwater could be produced, at a consumption rate of 6.26 kWh/m^3 (Gude, 2020).

A major disadvantage of this system, in comparison with other desalination devices, is the need of a clean feed to avoid damages. Raw seawater can contain suspended solids that, if not filtered, could damage the high-pressure pump or the membranes. Reverse osmosis systems are generally equipped with screens, gravity filters and micron cartridge filters that remove particles larger than 10 μm. This filtration set provides protection to the osmosis unit but places a higher workload to the crews, in comparison with other desalination systems (Khawaji et al., 2008).

Exhaust gas direct systems

The use of turbines directly applied to the exhaust gas stream is a well-known energy recovery system. This is the case of the classical turbo-compressor and also the base of power turbine generator systems.

Power turbine generator

Manufacturers like MAN Engines have proposed the installation of a WHR system that consists of a power turbine placed on the exhaust gas

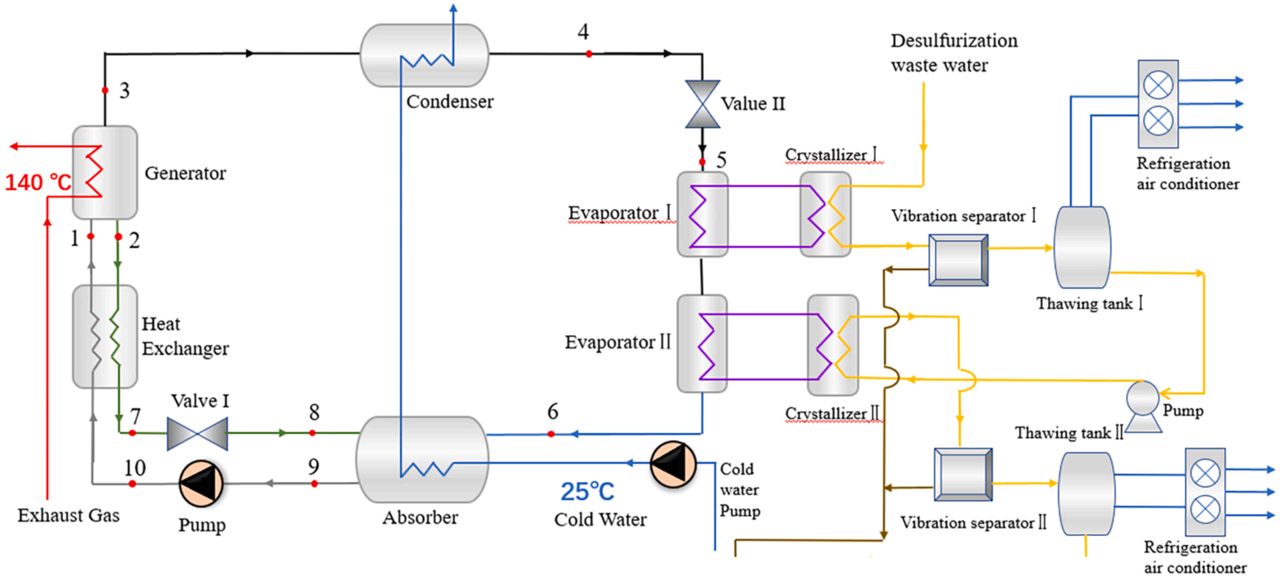


Fig. 20. Absorption refrigeration cycle coupled with two-stage crystallization system for freezing desalination. Adapted from (Ni et al., 2023).

bypass. This turbine has an electrical generator attached that converts the waste energy contained into the exhaust gas that has not passed through the turbo-compressor in electrical power (MAN, 2014). The reason behind this use is that turbochargers have very high efficiency so the power needed for compressing the inlet air can be extracted from a portion of the exhaust gas, dedicating the rest to power generation (Shu et al., 2013). The main disadvantage is the fact that the exhaust gas bypass valve will be only opened when the engine reaches a certain amount of load, not being useful in the whole range of engine load. In Fig. 21, a power turbine generator is fed by the exhaust gas current of a marine diesel engine.

In this review, two authors proposed a power turbine system as part of their WHR systems. Ma et al. used a system known as combined turbines, where a power turbine generator is combined with a steam turbine. Such system gained in complication, but it is estimated to produce approximately 10% of the engine power. With their proposed WHR system, Ma et al. increased the total thermal efficiency of the system from 50.6 to 53.8% (Ma et al., 2012). Qu et al. experimented with a WHR system comprised of a power turbine, a conventional steam Rankine cycle plus an ORC. Measured values of the power turbine generated power exceeded 100 kW, which contributed to the 1079.1 kW of power recovered while the engine operates at 100% load. This amount of power, on the MAN 6S50ME-C8.2 engine where it was tested (with a full load shaft power of 9960 kW), represented a 10.83% (Qu et al., 2021).

The system is very suitable for vessels that maintain stationary high loads on their engines but if constant load changes occur, the power turbine generation will be affected. The output of the power turbine directly depends on the exhaust gas mass flow of the engine and the needs of its turbocharger so at low loads the excess of exhaust gas mass flow may not be enough to operate the power turbine. For this reason, the system may not be suitable for vessels operating in slow steaming mode, below 60% load (Dzida and Mucharski, 2009).

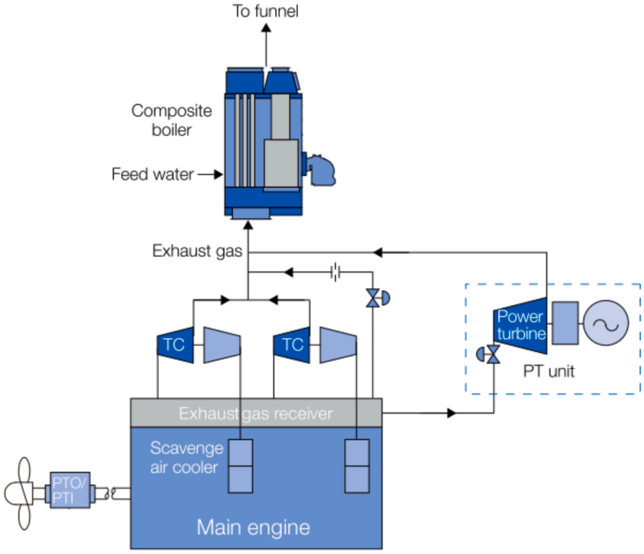
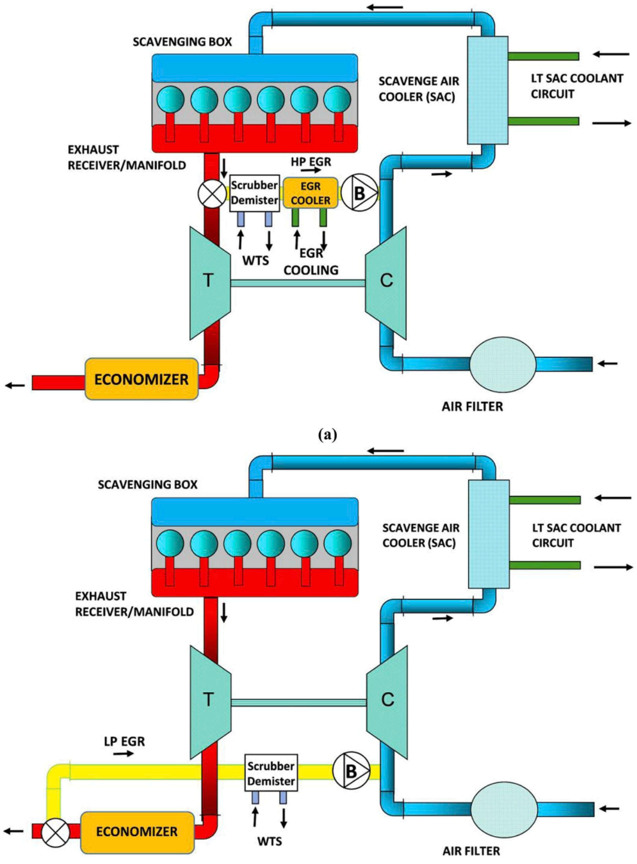


Fig. 21. Power turbine generator recovering waste heat from the exhaust gas of a marine propulsion engine (MAN, 2014).

Exhaust gas recirculation

This technique is more specific of emission reduction technologies, but some authors have included it in their studies. The system has been successfully applied in order to reduce NO$_x$ emissions because of its capacity to increase the specific heat capacity of the charge, reducing the in-cylinder temperature and decreasing oxygen concentration, which ultimately leads to a slower production of NO$_x$. On the other hand, it is known that exhaust gas recirculation (EGR) technology increases the specific fuel consumption and the soot formation rates (particulate matter), which is another environmental hazard (Raptotasios et al., 2015). Based on these criteria, Lion et al. proposed a combination of an ORC and a EGR system in order to achieve Tier II fuel consumption levels while reducing NO$_x$ emissions (Lion et al., 2019). In this case, Lion et al. used a low pressure EGR loop, installed after the turbo-compressor, where the exhaust gas has already been expanded. Conversely, Kyriakidis et al. presented a WHR system that integrated a steam Rankine cycle with a high pressure EGR loop, as the exhaust gas did not pass through the turbo-compressor, but with same successful results as the combination of an EGR system with WHR technologies will facilitate compliance with newest IMO regulations (Kyriakidis et al., 2017). In Fig. 22, the differences of high and low pressure EGR systems can be observed.

The use of low pressure is generally feasible since the pressure of the exhaust after the turbocharger is still higher than ambient air but low pressure EGR loops can bring issues like the fouling of diesel exhausts. Conventional compressors and charge air coolers are not designed to work with the high temperatures and the fouling of the diesel fumes. So, in order to apply a low pressure EGR as WHRS, changes into the air circuit components of the engine should be done (Zheng et al., 2004). Due to the related problems, it is desirable to implement a high pressure EGR loop. The complication here comes from the charge air pressure: if it is higher than the exhaust gas pressure additional means will need to be included in order to assure the injection of exhaust gas in the charge air current. In general terms, EGR is an interesting technology to combine NO$_x$ reduction and waste heat recovery but a solution with drawbacks as by itself cannot fully eliminate NO$_x$ emissions (Lu et al., 2020).



(a)

(b)

Fig. 22. Exhaust gas recirculation systems installed on the high pressure (a) and low pressure (b) sides. Adapted from (Lion et al., 2020).

Thermoelectric conversion

The use of the Seebeck effect has also been considered as a valid WHR technology and studied by some authors. This thermoelectric effect uses a thermocouple made by dissimilar metals or a semiconductor P-N pair that generates electricity when its ends are exposed to a temperature gradient (Ong et al., 2018). The efficiency of thermoelectric device depends on the figure-of-merit of the thermocouple material, usually represented by zT. Modern thermoelectric devices are fabricated using semiconductors of different materials that achieve high zT at different temperatures. Due to this, when designing a WHRS based on thermoelectric generation, the temperature of the heat source needs to be carefully observed. Recovery of heat at low temperatures, below 200 °C, will be favored by using a Bismuth Telluride (Bi_2Te_3) thermocouple meanwhile medium temperature heat sources, from 200 to 500 °C, need other materials like the Te-Ag-Ge-Sb (TAGS) alloy (Singh and Pedersen, 2016). This particularity of thermoelectric conversion represents an advantage as any grade of heat can be recovered with this technology but at the same time it is a drawback due to the lack of flexibility to recover different grades of heat. In order to maximize energy recovery, the contact between the heat source and the thermoelectric module needs an interface fluid with high thermal conductivity. Fig. 23 displays a thermoelectric generator and its inner thermocouples.

Kristiansen and Nielsen explored the possibilities of installing thermoelectric generators in order to recover the waste heat of a vessel and concluded that many sources like exhaust gas, scavenge air, jacket water and lubrication oil from the marine engine had potential. Also, in other auxiliary equipment like the ship incinerator, thermoelectric generators could be applied in order to recover waste heat from its flue gas or from the excess steam produced by marine boilers (Kristiansen and Nielsen, 2010). In a later study, Kristiansen and Nielsen performed a numerical simulation and concluded that 37.6 kW of waste heat from the exhaust gas of a marine incinerator could be recovered (Kristiansen et al., 2012). Later, Gude et al. proposed the application of the electric power generated by a thermoelectric WHR system to a RO desalination machine. The study showed that a wide variety of waste heat sources like the marine engine, incinerator, boilers and the fresh water evaporator could be used and 133 kW could be generated with the data of his case study (Gude, 2020). In this way, thermoelectric conversion can be advantageous to recover waste heat of a wide range of marine machinery and applied to different heat sources inside the marine engine (Díaz-Secades et al., 2023). Apart from the application to conventional and new heat sources, the thermoelectric conversion has silent operation due to the lack of moving parts, is scalable and virtually maintenance-free.

Cold energy recovery

Cold energy recovery could also be considered as a way to recover energy and improve system's efficiency but in this case, the recovery comes from the vaporization of LNG before it is supplied to the marine engine. This way of energy recovery is then limited to marine dual-fuel engines that are able to use LNG. Su et al. implemented this solution in a cascade WHR system composed of a supercritical CO_2 cycle and an ORC. Cold energy extracted from the LNG supply to the engine was used in freezing desalination and CO_2 liquefaction processes in order to produce fresh water and reduce emissions to the environment, respectively (Su et al., 2020). Ouyang et al. also explored the possibilities of cold energy recovery, placing liquefied-air energy storage and a sewage purification system. These devices achieved a storage of 36.97 kW of energy and the treatment of 368.25 kg/h of sewage which proved that cold energy recovery is an advisable way to recover energy in ships (Ouyang et al., 2020b). A general diagram of a cold energy application can be observed in Fig. 24.

Other applications

The following technologies have also been explored in order to maximize WHR from marine diesel engines. In the cases presented, all of them worked as a complement of main thermodynamic cycles and were implemented to extract the lowest temperature waste heat.

Trilateral cycle

The trilateral cycle can be considered as a variation of the conventional Rankine cycle where the turbine is replaced by a two-phase expander. Steam produced from the vaporization of water on the heat exchanger enters the two-phase expander reaching the wet vapor region. Depending on the temperature applied to the system, thermal efficiency of the trilateral cycle will be higher or lower than basic ORC, improving the trilateral cycle when evaporation temperatures exceed 130 °C (Li et al., 2017). For better understanding of this thermodynamic cycle, Fig. 25 displays the T-S diagram of an organic trilateral cycle proposed by Ouyang et al. where steam was replaced by an organic fluid.

In this review, two authors have included the trilateral cycle as part of their WHR systems. The research carried by Ouyang et al. where the organic flash cycle was investigated, proposed also the use of an organic trilateral cycle using R245fa as well. In this case, the trilateral cycle yielded the lowest performance of the three options (ORC, organic flash and organic trilateral cycles) (Ouyang et al., 2020d). Choi and Kim studied a system where a steam trilateral cycle was coupled with an ORC in order to recover the waste heat present in the exhaust gas of a containership diesel engine and concluded that the overall WHR system improved engine's efficiency in 2.824% (Choi and Kim, 2013).

Organic flash cycle

The organic flash cycle is a modification of the organic version of the trilateral cycle. This is a steam power cycle than can improve the efficiency of the system as it is designed to improve temperature matching and reduce exergy losses. A flash separator is used to divide the saturated liquid in two phases, and meanwhile the steam is expanded in a turbine, the liquid fraction is diverted to another bottoming cycle

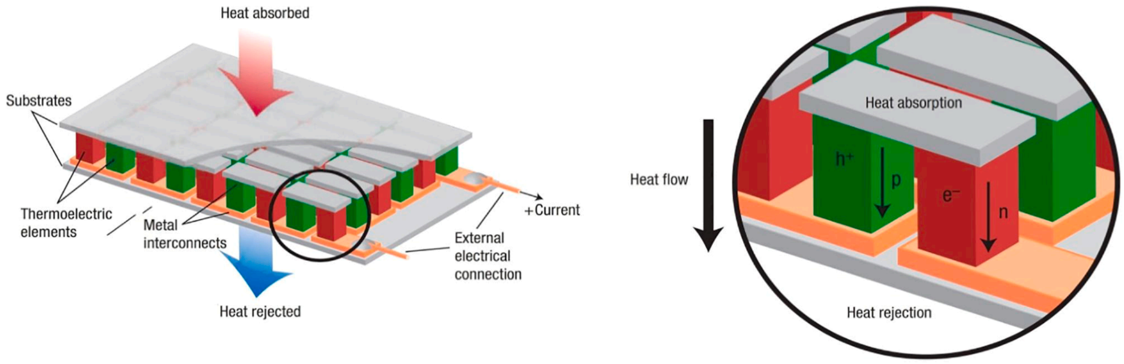


Fig. 23. Thermoelectric generator. The heat flowing across the module will be converted in electrical energy in the electrical terminals (Douadi et al., 2022).

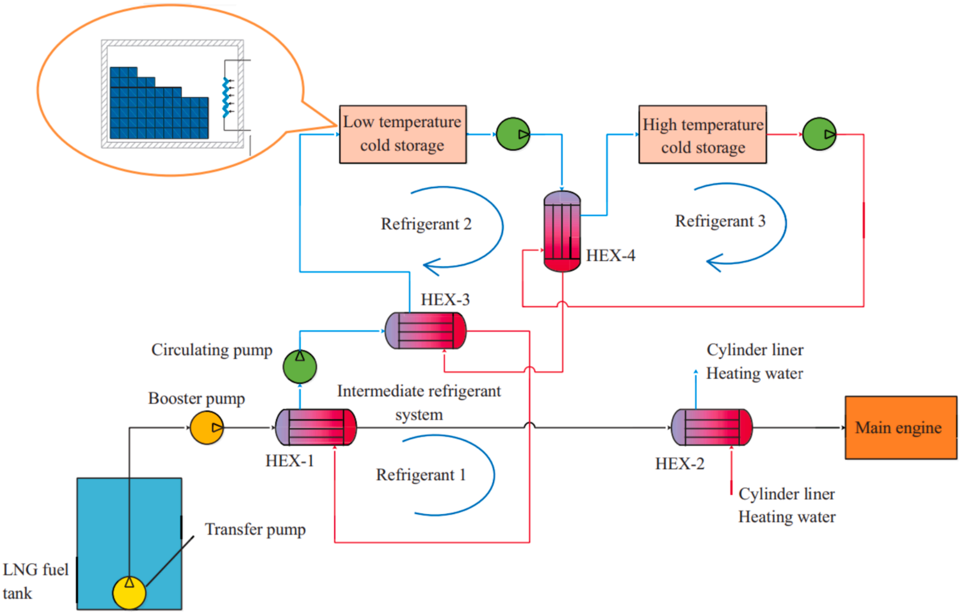


Fig. 24. Diagram of a cold energy application proposed to satisfy the cooling needs onboard a vessel equipped with dual-fuel engines (Li et al., 2022).

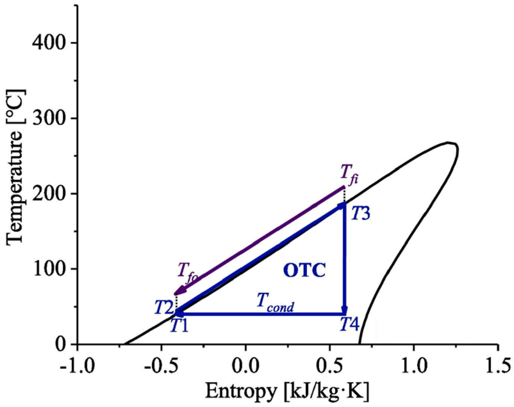


Fig. 25. T-S diagram of an organic trilateral cycle. Adapted from (Ouyang et al., 2020d).

(Weitzer et al., 2022). This configuration provides a better temperature matching with the heat source, what could increase efficiency. A layout of a simple organic flash cycle, which uses an organic fluid instead of water steam, is shown in Fig. 26.

Ouyang et al. studied a three cycle-configuration system for the recovery of waste heat from the exhaust gas of a marine diesel engine that had an organic flash cycle working with R245fa recovering the low-grade heat that remained on the exhaust gas after passing through a supercritical Brayton cycle. During its research, an ORC and an organic trilateral cycle were also tested, all working with the same organic fluid. Out of the three options, and under the same conditions, the combination of the supercritical Brayton with the ORC was the most competitive, increasing energy efficiency in a 4.66% (Ouyang et al., 2020d). In another study, the same author proposed a sequential system where a supercritical Brayton was followed by an organic flash cycle and an absorption refrigeration cycle in that particular order. The different cycles that composed the WHR system that recovered exhaust gas waste heat from a marine diesel engine but when comparing the organic flash cycle with the absorption refrigeration, Ouyang et al. concluded that the contribution of the absorption refrigeration system to the WHR was greater than the organic flash cycle while both work below 200 °C (Ouyang et al., 2020b). The greatest drawback of this cycle is related to the large exchanging surface required to heat the fluid. This issue becomes relevant when applying the technology into a vessel, since available space onboard is already scarce.

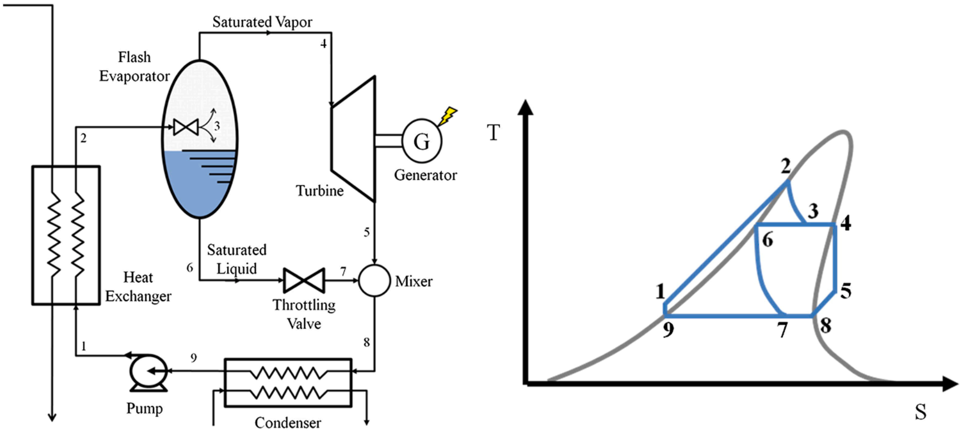


Fig. 26. Layout diagram of a simple organic flash cycle along with its T–S (Ho et al., 2012).

Solid oxide electrolyzer cell

The solid oxide electrolyzer cell allows for the efficient conversion of electrical energy into chemical energy in the form of hydrogen by means of water steam electrolysis. This technique is achieved at high temperatures, 500–1000 °C, and is considered to be a worthwhile technique to produce hydrogen due to its reduced electrical consumption if compared to low temperature water electrolysis (Cai et al., 2012). The production of hydrogen and more specifically, green hydrogen will be a much-demanded technological solution in the following years and SOEC systems coupled with external waste heat sources have been found the most economical alternative (Jang et al., 2022). Wang et al. explored a further use for the waste heat produced by the marine engine in a SOEC system coupled with an ORC in order to produce hydrogen from the exhaust gas and engine cooling water waste heat. The issue with the application of this technology is that steam electrolysis requires vaporized water and electricity to work. Even if the electricity for the electrolyzer cell is fully extracted from the ORC turbogenerator, waste heat may not be enough to vaporize the stream of water needed and rise it to the operating temperature the SOEC demands. Being aware of this problem, Wang et al. proposed the installation of an electric heater in order to compensate any additional required heat (Wang et al., 2021).

While SOEC technology is an interesting way to recover waste heat, the high operating temperatures result in thermal expansion and contraction, which could cause mechanical stress on the cell. This can lead to degradation and shorten the lifespan of the system. The breakdown of the cell and its high operating temperatures should be considered as a risk to operators when installing it onboard vessels.

Conclusions and future developments

The increase on production efficiency on the maritime transport becomes essential due to the importance it has for international trade. On marine engines, an increase in efficiency by improving the internals of the engine has reached a point where much research is needed for very little improvement. However, waste heat recovery has been proven as a valid and successful technique to increase efficiency and reduce both fuel consumption and greenhouse gasses emissions.

Previous works presented the development of the most common thermodynamic cycles used to recover waste heat from the exhaust gas of marine engines. There was a literature gap in terms of review issues related to the recovery of low-grade waste heat, present case studies and relate country-specific situations. Nowadays, high technology readiness level (TRL) applications have potential to recover waste heat from marine engines' alternative heat sources. To fill this gap, the following research questions were asked: (Q1) Which WHR systems are already applied or studied for its use on marine engines?, Q2: Is there any gap in the knowledge, in terms of current developed but not applied technologies or missing waste heat sources, that is worth to be explored?, (Q3) Which of these proposed systems might provoke a breakthrough in the industry?. To answer these questions, an initial quantitative bibliometric analysis was conducted in order to understand the organization, structure and relations among studies on the domain research. Secondly, a systematic review following the PRISMA 2020 approach was performed. A total of 1049 previous works were identified and screened, out of which 576 were assessed by means of a bibliometric analysis. Finally, 35 journal articles were included in a qualitative synthesis. Seventeen different technologies to recover waste heat from five different waste heat sources were studied.

This study shows the directions followed by researchers as well as the most popular technologies and alternative options that can be used for WHR and thereby decarbonization. The work also explores which authors and countries are the most scientifically prolific, their collaboration with other research groups and countries and the importance of these nations in the maritime trade. Policymakers and technologists could use it in understanding and developing decarbonization action plans. The main conclusions of this work are:

1) Q1: The 17 WHR technologies analyzed in this paper have been applied to marine diesel and dual-fuel engines. Cold energy extraction from the vaporization of LNG is a good energy recovery strategy but limited to dual-fuel engines. The studied systems differ in their applicability, complexity and grade of heat they are able to recover but a combination of several of them can increase notably the efficiency of the marine diesel engine. On the other hand, each application has its own drawbacks: conventional Rankine and Brayton cycles are designed for high temperatures and the only suitable heat sources on the engine are exhaust gas and scavenge air. Conversely, organic cycles plus variations like Kalina, Flash and Trilateral work with organic fluids, which are able to extract low-grade heat. From an environmental point of view the use of organic fluids needs to be observed since global warming potential of organic fluids can be hundreds of times higher than CO_2. Some working fluids like ammonia do not contribute to the greenhouse effect (GWP = 0), but they are harmful for humans. Fatalities on board of ships equipped with ammonia systems, mainly for refrigeration purposes, have already occurred.
2) Q2: In general terms, the study of waste heat recovery using thermoelectricity has not been widely explored and presents advantages like being a vibration-free, leak-free, durable system. Only Kristiansen and Nielsen explored its possibilities and later Gude proposed a method to harvest and reuse the recovered energy. On top of that, the extraction of lowest-grade heat is still a challenge. The recovery of waste heat from lubrication oil has only been investigated in five publications out of the 35 analyzed. Other waste heat sources like the heat carried by the return fuel lines or the heat dissipated by the engine block were not mentioned until 2022, when Díaz-Secades et al. analyzed them. Vessels undergoing a fuel conversion due to the IMO2020 policy encountered the need of installing a marine diesel oil (MDO) plate cooler as the temperature reached by the fuel became excessive.
3) Q3: After this review, the authors conclude that not one unique system will be the best option to maximize the recovery of waste heat but a combination of several devices. Depending on the quality of heat, a thermodynamic cycle can be combined with absorption refrigeration, thermoelectricity and, if possible, cold energy recovery. The installation of many systems to recover exhaust gas waste heat is not highly recommended since those systems will increase the backpressure on the exhaust line and thus, the fuel consumption of the engine. In that case, a combination with an emission reduction system like EGR should be considered. Also, consideration of the limit temperature to avoid acid dew point should be observed. For the rest of heat sources, the maximization of waste heat recovery should be analyzed under two conditions: simplicity of the system as engine room crew hands are limited and correct operation of the engine as if heat from jacket water or lubrication oil is extracted in excess, a worse combustion or poorer lubrication will have place, respectively.

In general, the authors have noticed that a proper comparison between different studies is somewhat difficult as each author express their findings in a different metric. A standardization, using first and second laws of thermodynamics to express efficiency is recommended.

The authors of this article are aware of their limitations when producing this work. The article is written from a clear technology perspective, analyzing each WHR option separately and focusing on the merchant marine sector. Waste heat recovery on other vessels, like military, would need a different approach as they use different propulsion systems. Also, the combination of several technologies might bring different effects than the simple sum of individual systems. Without the regulators agreement and a solid mid-term plan to decarbonize the maritime industry, there is a risk that only straightforward, short payback systems will be implemented, with limited environmental benefits. In view of the results of this study, a further investigation on low TRL technologies is needed in order to maximize future commercial options.

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

No data was used for the research described in the article.

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