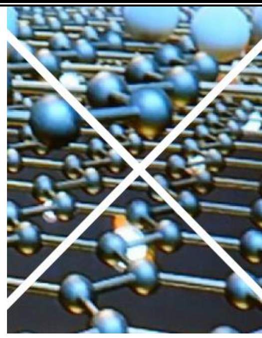
TIJMET, Vol. 0004 (2021) 133-146

The International Journal of

Materials and Engineering Technology

ISSN: 2667-4033
TIJMET ID: 210402006 (14 pages)
Type of the Paper: Comparative Assessment
Received: 18.11.2021 Revised: 21.12.2021 Accepted: 23.12.2021 Published (Online): 25.12.2021
Journal homepage: http://dergipark.gov.tr/tijmet



ENERGY, ENVIRONMENT AND ECONOMY ASSESSMENT OF WASTE HEAT RECOVERY TECHNOLOGIES IN MARINE INDUSTRY

HASAN MITHAT DELIBAS[*1a], ERHAN KAYABASI [2b]

[1]Hasan Kalyoncu University, Engineering Faculty, Mechanical Engineering, Gaziantep, TURKEY.
[2] Karabuk University, Engineering Faculty, Mechanical Engineering, Karabuk, TURKEY.
[*]hmithat.delibas@hku.edu.tr

Abstract

In this study, an assessment and comparison of the Waste Heat Recovery (WHR) systems in maritime industries are made in detail in terms of energy, environment, and economy (3E) analysis. WHR systems are assessed according to types and stroke engines, thermodynamic cycles, waste heat source, types of fluid, heat exchangers, and the pollutants released into the atmosphere by the exhaust gas. Furthermore, while examining WHR systems, criteria such as feasibility, initial investment costs, depreciation periods, depreciation rates, possible energy recovery are considered. It is noteworthy that such an assessment has not been conducted so far in the comprehensive literature researches. Therefore, this study will determine the most appropriate waste heat recovery systems in marine industries.

Keyword: Waste heat recovery (WHR), Marine industries, Energy savings, Thermodynamic cycles, 3E analysis

1. Introduction

To reduce energy consumption, production costs and environmental impacts, heat recovery systems are critical auxiliary tools for the sectors that use thermal energy. The marine industry is one of the most energy-intense sectors [1]. It should not be overlooked that one of the essential factors in the country's economy is export performance. Considering that the global trade volume has increased even more than 100% compared to the 20th century, the importance of logistics competence in global trade is increasing day by day. [2]. Today, the use of marine sectors has increased due to the increasing market of the global economy. With an annual volume of 11 million tons, the marine industry provides more than 90% of World Trade. It is expected that trade volume will grow by 3.4% annually between 2019-2024, leading

How to cite this article:
Delibas, H.M., Kayabasi E., Energy, Environment and Economy Assessment of Waste Heat Recovery Technologies in Marine Industry, The International Journal of Materials and Engineering Technology, 2021, 4(2): 133-146.

ORCID ID:
[a]0000-0003-3353-8600, [b]0000-0002-3603-6211

to increased gas emissions and energy needs [3]. In large-volume industrial engines, when the fuel atoms in the combustion chamber cannot combine with the oxygen atoms, the combustion quality deteriorates. Therefore, carcinogenic substances such as nitrogen oxides (NOx), carbon moNOxide (CO), unburned hydrocarbons (HC) are released into the atmosphere through the exhaust gas [4]. Ocean-going ships often have diesel engines that use cheap heavy fuel oil (HFO) containing significant amounts of sulfur and, if used, cause high amounts of sulfur oxide (SOx) emissions. [5]. Sulfur oxide (SOx) gas harms both human health (respiratory diseases) and environmental conditions (acid accumulation). Strict legislation, Annex VI of MARPOL, was enacted to reduce emissions from marine engines in 2015 [6]. With MARPOL, Annex VI is intended to restrict the release of ozone-damaging substances into the atmosphere, including sulfur oxides (SOx) and nitrogen oxides (NOx) from ship exhaust gases [7]. In this context, sulfur gas emissions are projected to be reduced by 0.5% after 2020. Distilled fuels have far lower emission rates than heavy fuels but are almost 50% more expensive. Therefore, the most efficient way to achieve the permitted emission rates following the regulations is to apply a finishing process that dissociates sulfur-oxide gas from exhaust gas formed by HFO. In this way, cheap and efficient heavy fuels can continue to be used or efficient heat recovery systems to reduce total emissions from exhaust gases. Studies are available in the literature to reduce the emission of ship exhaust gases. Conventional flue gas desulfurization (FDG) methods usually have two different ways as dry and wet methods. Literature studies show us that the use of wet methods is more attractive. In the wet method, limestone slurry is often used as sorbent. Sulphur-oxide reacts with sorbent to form a precipitate, and thus the exhaust gas is purified from sulfur [8].

Another example that can be given for the wet method is the use of seawater. Natural essential components in seawater act as sorbents and react with sulfur-oxide to form a precipitate [9]. However, while studies are carried out to reduce the emission values of flue gases, it should not be ignored that there is a high amount of waste heat in their contents. The recycling of waste heat energy is essential for engineering operations while the emission removal processes are being carried out. Ozcan and Kayabasi [10] in their study with flue gases containing high energy and emission show that 1.5 MW power generation is possible using heat recovery systems with the Kalina cycle. Therefore, it is inefficient to use only traditional methods in emission reduction studies, especially in high-input areas such as marine industries.

The operating cost of modern ships, fuel costs occupy approximately 43% and 67%, depending on the type of ship [11]. However, despite these high costs, today's large modern engines have only 50% efficiency in using thermal fuel energy [12]. This massive imbalance in the cost-efficiency ratio is essential for the marine industry. Therefore, business owners need to reduce emissions from flue gas and increase fuel efficiency to the highest possible level in the marine industries. Literature studies have shown that studies have been done on reducing auxiliary power consumption, developments in travel practice, use of air-guiding elements, development of system designs, etc., to increase fuel economy [13]. It is noteworthy that today's studies focus on developing new waste heat recovery systems (WHR). It has many advantages, such as fuel-saving, improving system efficiency, and reducing flue gas emissions, making WHR systems attractive. WHR systems ensure that the energy sent from the flue gas to the atmosphere is recovered at high rates, and emission removal is achieved successfully. Therefore, the most crucial focal point in reducing the emissions of flue gases should be WHR systems. The mechanical or electrical power can be obtained with this recovered heat energy, and the main engine load can be reduced [14].

Many methods for waste heat recovery have been developed in marine industries. The research and development in this area are mainly focused on the following techniques: Exhaust gas turbine system (EGT), thermodynamic Organic Rankine cycle (ORC), Kalina cycle (KC), and thermoelectric generators (TG) [15]. Zhibin Yu et al. [16] combined a system containing ORC and Vapour Compression Refrigeration (VCR) and produced comprehensive energy and Exergy analysis. S. Bellolio et al. [17] Designed an ORC-based system to recover waste heat from multiple heat sources. Their simulation results show that with the use of ORC, efficiency increases and emission rates decrease. In their study, Platon Pallis et. al [18] led us to the trial procedure and improvement phases of an ORC prototype working with R134a that they developed. This prototype's main idea is to recover the waste heat from jacket cooling water, which temperature is approximately 85 °C, of a marine diesel engine, using seawater as a heat sink. They found that the developed prototype's 24-hour average nominal net efficiency was 4.59% higher than conventional engines. Thus, based on baseline reviews, the amortized payback period was found to be 11.54 years. Waltteri Salmia et al. [19], with their work, have shown us that up to 90 tons of fuel can be saved per year and that an efficiency increase of up to 4 times can be achieved. Tao Cao et al. [20] have developed system analysis by designing an onboard absorption cooling system using the engine waste heat on a cargo ship. System analyses were performed according to many different climate characteristics, and the COP value can be subtracted from 3.6 to 9.4. Furthermore, there has been a 62% decrease in CO_2 emissions. Chun Wee Ng et al. [21] proposed and modeled an ORC system using n-heptane or n-octane as the working fluid. The modeling results show that a system with a depreciation period of 2.7 years and 7% annual fuel savings can be designed. Enrico Baldassoa et al. [22] investigated the possible consequences of establishing an ORC system on a feeder ship with a dual-fuel engine that is assumed to be powered by natural gas. The research results showed that the orc system would be more cost-effective on large container ships with 6500 hours of activity annually and running in slow steaming mode. Jian Song et al. [23] offer an optimized ORC system that uses jacket cooling water as a preheat medium and uses engine exhaust gas to ensure evaporation to facilitate waste heat recovery. The following two topics were evaluated in the study: the effect of preheating temperature on system performance, defining the optimum working condition. Ulrik Larsen et al. [24] a system analysis was conducted by research to increase the temperature harmony between the heat source and the working fluid using Split-cycle (SC) and KC system. KC and SC systems were compared with each other in this study. The study results show that SC systems are 3.4-5.9% more efficient than conventional KC systems. However, complex system elements negatively affected the purchase cost and increased the initial investment cost.

Considering the importance of the marine industry, the fact that WHR systems used in marine industries have not been studied as a whole in terms of energy, environment, and economy up to now stands out as a significant flaw in the literature. Review or assessment studies examining WHR systems from an energy perspective are limited to Gequn Shu [25] and Dig Vijay Singh [15]. In addition, Ju-Yong et al. [26] have taken a limited approach to WHR systems by comparing results from studies based on Hierarchy-Grey correlation analysis in the marine industry. This study assesses the use of WHR systems in the maritime sector. These assessments are types and strokes of engines, thermodynamic cycles, waste heat source, work fluids, heat exchangers devices, and the number of pollutants. While examining these systems, criteria such as feasibility, initial investment costs, depreciation periods, depreciation rates, and possible energy recovery amounts were considered. This study aims to determine optimum WHR systems by comparing the energy, environmental, and economic results.

2. Usage Methods of WHR Technologies

Many different types of WHR systems can be used in the maritime industry. WHR systems can be assessed according to the engine type and stroke used by the marine machinery, the types of working fluids, the preferred heat exchanger type, and the exhaust gas emission conditions released into the atmosphere.

2.1. Differences of the Engine and Stroke Types

For a vessel that uses large diesel engines to provide the main mechanical power in the marine industry, the most significant waste energy is the heat lost by the exhaust gas. Today, almost 80% of sea vessels use two-stroke marine engines, while the remaining 20% use four-stroke engines [27]. Figure 1 shows the energy values of a large two-stroke diesel engine. As indicated in Figure 1, almost 50% of the fuel energy is released into the atmosphere without any benefit [12]. In addition, the exhaust gas discharge temperatures have different values for two types of engines. For a marine vessel with a standard 2-stroke engine, the exhaust emission temperature ranges between 325-345 °C, but for 4-stroke engines, it can rise to 400-500 °C [28].

Theotokatos and Livanos [29] studied the operating conditions of WHR systems saturated steam and electric power generation. It was assumed that the WHR system used an external heat exchanger with a single vapor pressure type to heat the boiler's feed water. In addition, the use of an engine air cooler for heating the feed water was also investigated. The main finding of this study is that a complex WHR system combined with two-stroke engines gives much better results. It has also been found that heating the feed water with saturated steam significantly reduces WHR efficiency and lowers net electricity generation. In a system with a two-stroke engine, 340 kW of electrical energy is generated if the feed water is heated using the engine air cooler.

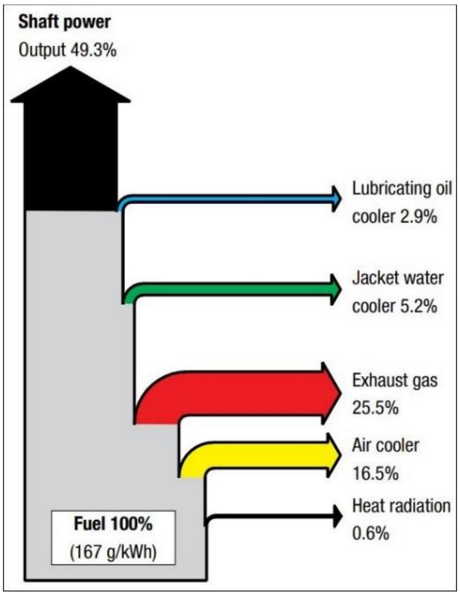


Figure 1. Heat balance for a standard model marine diesel engine with ISO conditions [12].

R.F. Nielsen et al. [30] investigated a combined waste heat recovery system consisting of a two-stroke low-speed diesel engine and a double-pressure steam cycle. With this study modeling a new WHR system, having 75% maximum continuous rating primary motor load ratio is based on a system. The proposed system uses heat from the exhaust gas in the ORC after the sulfuric acid is removed from the exhaust gas before being sent to the environment. This way, it resulted in a 33% increase in the WHR efficiency for the system using R245fa as the working fluid. This results in a 2.6% increase in the efficiency of the all integrated system.

2.2. Differences in the Types of Thermodynamic Cycles

While providing heat recovery with the help of WHR systems, it uses many thermodynamic cycles to obtain usable energy, reduce emissions, etc. The literature studies on this subject show us that today's literature focuses on 4 main cycles, such as; organic Rankine cycle (ORC), Rankine cycle (RC), Kalina cycle (KC), and steam cycle (SC). The flow diagrams of these cycles are as shown in Figures 2-4, respectively [14].

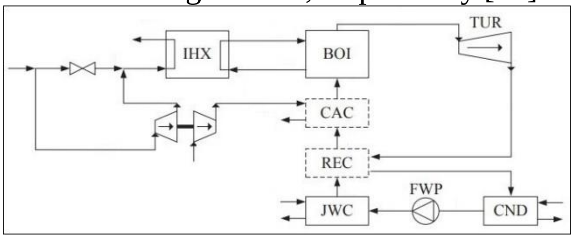


Figure 2. ORC process flow diagram [14].

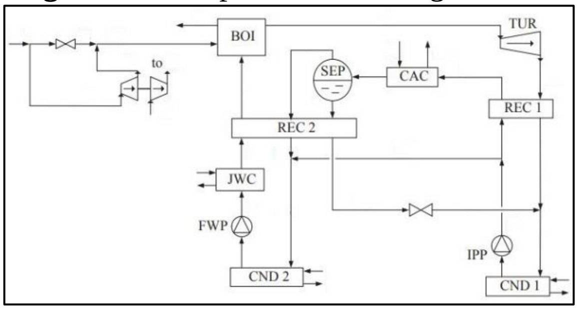


Figure 3. KC process flow diagram [14].

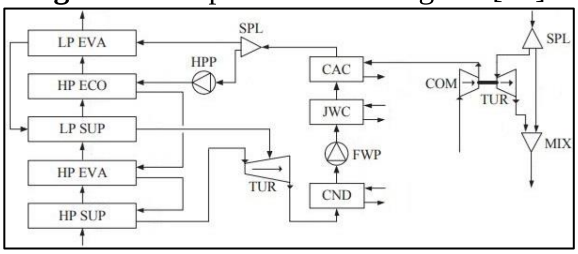


Figure 4. SC process flow diagram [14].

Ulrik Larsen et al. [14] combined ORC, KC, and SC systems on a two-stroke marine diesel engine and made comparisons between cycles. These comparisons were made using numerical modeling using an algorithm based on the MATLAB program. According to the results, a cycle with an ORC system has an additional power contribution of about 7%. This ratio was found 5% in cycles with KC or SC system. The generated algorithms predict that the ORC WHR system can reduce specific fuel consumption from 170.6 g/kWh to 162.2 g/kWh.

Zhibin Yu et al. [16] investigated the possible consequences of integrating the ORC system into a vapor compression cycle (VCC) refrigerator system to provide an alternative to absorption refrigeration systems on ships where a cooling system is used required. The main idea of the system schematized in Figure 5 is to transmit the mechanical power obtained by the Orc system to the compressor of the refrigeration cycle. The data show that the proposed system can achieve a cooling capacity of 9823 kW at 263 K temperature. Furthermore, values tend to increase with increasing engine load. Thus, findings show that the proposed system is promising for the future.

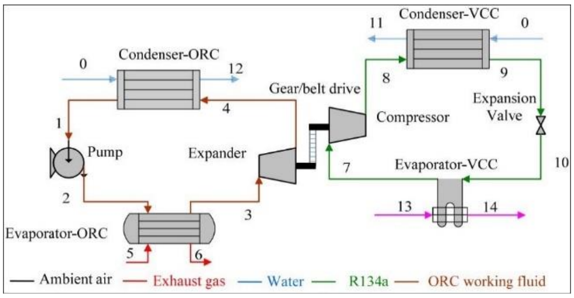


Figure 5. Schematic of proposed ORC-VCC integrated system [16].

Ziyang Cheng et al. [31] proposed a new cogeneration system based on the Kalina cycle and absorption refrigeration system to meet the design requirements, which efficiently meets the power and cooling demands of a marine vessel at the same time. The basic ammonia mass ratio of the system is increased. As a result, the ammonia-water vapor from the separator can have a higher ammonia concentration, contributing to a lower cooling temperature and less heat loss in the distillation process. Besides that, a higher ammonia concentration solution facilitates overheating, improving thermal efficiency. Cheng and others optimized this cogeneration system with the genetic algorithm to obtain the best performance. As a result of this optimization, the system receives 333.00kW of net power output, 28.83 kW of refrigerating capacity, and 21.81% of thermal efficiency. In addition, for comparing this new system is used a recuperative organic Rankine cycle and an optimized Kalina cycle using an identical heat source. The outcome of this comparison shows us power output and thermal efficiencies are at least 1.05% and 3.89%

greater than the ORC and KC systems for this cogeneration system, respectively.

2.3. Different Parts Used as Heat Source

In WHR systems, the component selected as a waste heat source is of great importance. The efficiency and capacity of WHR systems depend directly on the quality, stability, and thermal values of the heat coming from the source. As mentioned earlier, in marine industries, almost 50% of the energy gained from the fuel is released to the atmosphere as waste heat from the engine flue. Therefore, the capacity and power of the engine that emits the exhaust gas selected as the waste heat source is a point to be considered.

In his work, George Sakalis [32] investigated a marine diesel engine utilizing a supercritical CO_2 cycle for energy efficiency improvement. This work aims to recover the waste heat through three different sources: exhaust gas, compressed scavenge air, and jacket cooling water. This work aims to recover the waste heat through the three various sources: exhaust gas compressed scavenge air, and jacket cooling water and minimize the fuel consumption through the decreased propulsion load. Results of this study are shown us that it had been concluded that the energy conversion efficiency could be increased by approximately 6.6% to 7.25% compared to conventional diesel engines. In addition, according to this system design, it is predicted that a total of 12697 kW of energy can be recovered, including 353 kW from the jacket cooling water, 4606 kW from the scavenging air, and 7738 kW from the exhaust gas.

Tao Cao et al. [33] designed a waste heat-powered system for air conditioning and refrigeration on a container ship. They were made for cases where a WARTSILA 8RT-flex 68-D type motor with a nominal capacity of 25040 kW is used onboard. In this way, energy flows and exhaust gas indexes, which are essential for the performance of WHR systems, have been identified. The exhaust gas indexes include the exhaust gas temperature and the exhaust gas mass flow. According to the data, the system schematized in Figure 6 is expected to reduce fuel consumption and CO_2 emissions by 38%.

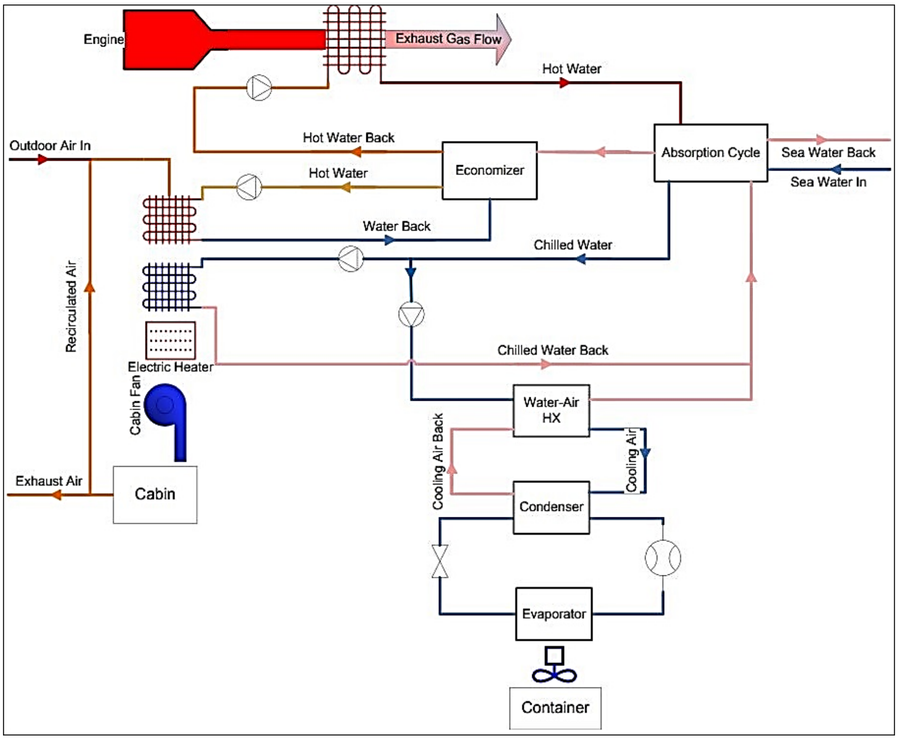


Figure 6. Schematic of the proposed combined system [33]

2.4. Differences in Working Fluid Selection

In WHR systems used in today's marine industries, it is crucial to produce useful energy even from low-temperature heat sources. Therefore, the demand has begun to direct the researchers to develop WHR systems in marine industries to system designs that accommodate low working temperature and pressure levels. In general opinion, ORC can be considered an optional promising system [30].

Vélez et al. [34] conducted ORC studies to obtain electrical or mechanical power from thermal energy at low and medium temperatures. As a result of the modeling, it is seen that ORC systems are very efficient, especially in systems operating at least 8000 hours per year as in sea vessels. However, the appropriate working fluid must have optimum thermodynamic properties at low temperatures and pressure. In addition, they must be economical, non-flammable, and environmentally friendly. Considering these broad aspects, it is noteworthy that suitable working fluids are minimal. According to the data, the most suitable working fluids were R11 - R113 - R114, but these are currently limited due to their adverse environmental effects. Therefore, it has been found that R245fa and R134a, without environmental damage, are good candidates for use in current ORC systems.

Chun Wee Ng et al. [21] modeling was made by proposing an ORC system using n-heptane or n-octane as working fluid. Modeling was performed for an ORC system, operated by an LNG engine, heated by engine exhaust, and cooled seawater. Although the n-heptane and n-octane liquids are not toxins, additional safety considerations are required as the flashpoints are below the engine room temperature, as shown in Table 1.

As a result of the study, as shown in Figure 7, it was found that the thermal efficiency and network output of n-heptane liquid was higher than n-octane liquid. In an ORC system working with n-heptane, the thermal efficiency and network output were found respectively, 23.46% was 176.18 kW /kg. Modeling results in 7% fuel savings per year with the ORC system with n-Heptane, and in this case, the system's payback period will be approximately 2.7 years [21].

Bashan and Kokkulunk [35] studied a case study ship to compare conventional VCR systems with VCR systems integrated WHRS. For this purpose, they used 15 different refrigerants and seawater with variable temperatures to compare the changes of exergy destruction, second law efficiency, COP, and emission. Additionally, they proposed a novel WHR system for increasing the quality of accommodation water using some preheating. This proposition can be lead to reducing the energy destruction by about 9.31–10.60% when using R134a as a refrigerant. However, the fuel consumption because of the refrigerant compressor can cause a 36% increase with a 10°C increase in seawater temperature. This increase could cause massive CO_2, SO_2, NOx, and Particular Matter emissions, and this ratio of increases is about 183.40, 3.10, 4.65, and 0.47 tons, respectively. The preliminary results of this study by made Bashan and Kokkulunk are as shown in Figure 8.

Table 1. Comparison of properties of proposed fluids [21].

	Formula	**$T_{fr.}$ (°C)**	**$T_{boil.}$ (°C)**	**$T_{cr.}$ (°C)**	**$P_{cr.}$ (bar)**	**Flash Point (°C)**	**Auto İgnition (°C)**
Methane	CH_4	-182.46	-161.49	-82.59	44.08	-187.2	536.9
n-Heptane	C_7H_{16}	-90.58	98.43	266.98	27.36	-4.1	203.9
n-Octane	C_8H_{18}	-56.77	125.68	296.17	24.97	12.9	205.9

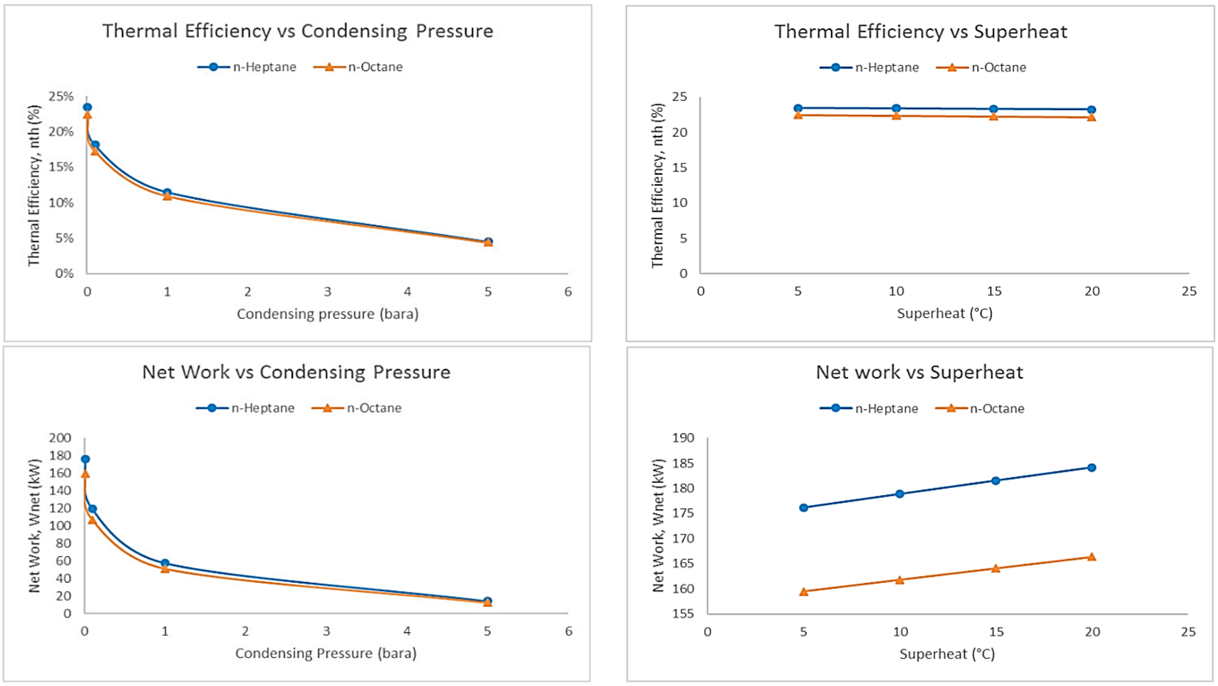


Figure 7. Cycle efficiency and net power output at proposed fluids [21].

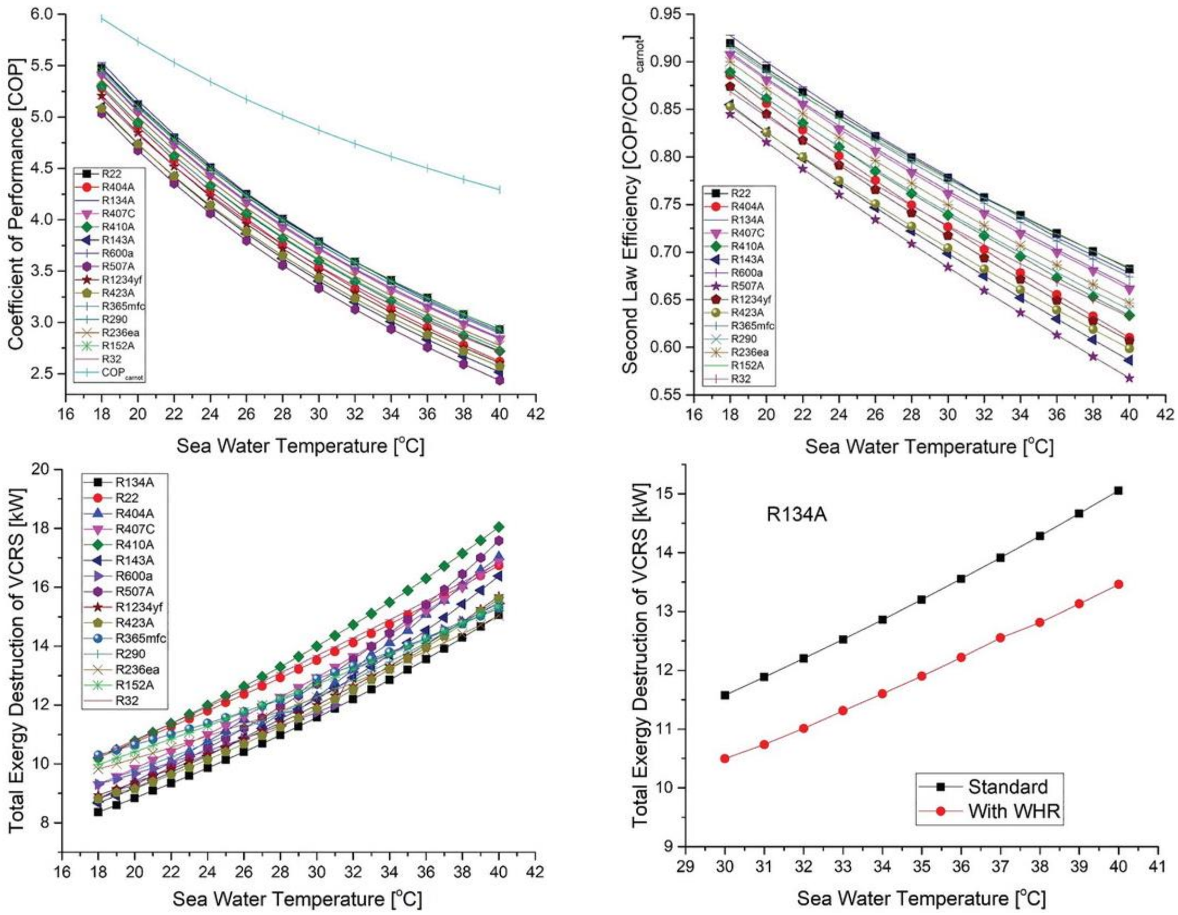


Figure 8. Changes of COP, Second Law Efficiency and Total Exergy Destruction according to different refrigerants [35]

2.5. Effect of WHR Systems on Emission Rates

MARPOL, Annex VI, was put into action in 2015 as strict legislation to reduce emissions from marine engines. In this context, it is planned that after 2020, sulfur gas emissions will be reduced to 0.5%. However, flue exhaust gases also contain very high levels of waste heat. Therefore, recycling waste heat energy is essential for engineering processes while performing de-emission operations. With the WHR systems, the energy released from the flue gas to the atmosphere is recovered at high rates, and emission reduction could be successful at the same time. Therefore, the most crucial focal point in reducing the emissions of flue gases should be WHR systems.

Fotis Kyriakidis et al. [36] have conducted studies to eliminate NOx emissions with waste heat recovery. The study includes the theoretical optimization of an integrated system based on exhaust gas circulation and two different steam Rankine cycles for a two-stroke diesel marine engine. The results show that a net power of 1577 kW can be generated from the two-pressure level steam cycle and 1641 kW from the three-pressure level steam cycle. Furthermore, in exhaust gas circulation, the emissions are cleaned and removed by the pre-scrubber. In this way, the exhaust gas emission quantity decreases up to the IMO standards.

Santiago Suárez de la Fuente et al. [37] compared a standard water-based Rankine cycle system with five different organic Rankine cycle systems using benzene, heptane, hexamethyldisiloxane, toluene and, R245fa. These comparisons are the efficiency of systems, the potential for reducing CO_2 emissions, and economic viability. The case study on a tanker ship shows us that establishing an RC integrated WHR system that works with organic liquids provides 705 tons of CO_2 emissions per year. Furthermore, in the simulation studies, it is observed that the organic Rankine cycle system offers the best performance in benzene-containing.

Tiancheng Ouyang et al. [38] proposed an integrated WHR system for a natural gas engine with several thermodynamic models. These models include the supercritical Brayton cycle (SBC), the absorption refrigeration cycle (ARC), the organic flash cycle (OFC). This study aims to ensure efficient waste heat and cold energy use and reduce energy costs and emission ratios. According to this study, the maximum power generation can be up to 1774 KW, and thermal efficiency can reach 40.23%. These outputs of the study show us that this engine-combined system provides approximately 215 kW more net power generation and 5.15% more thermal efficiency than conventional engines. At the same time, the emission reduction (CO_2) and fuel recovery can be reached to approximately 52 kg/h and 39 kg/h, respectively. Finally, the investment cost of this system can be recovered in almost 7 years.

3. Results and Discussion

3.1. Results and Discussions about Engine Type and Stroke Differences

Especially for WHR systems using exhaust gas as a waste heat source, the engine type and stroke type are vital. Because of the amount of heat recovery obtained, the electrical energy and mechanical power that can be obtained depends directly on the exhaust gas indexes. Therefore, exhaust gas indexes may differ according to the engine types used. For example, for a marine vessel with a standard 2-stroke engine, the exhaust temperature ranges between 325-345 °C, while for 4-stroke engines, this temperature can rise to 400-500 °C. Although four-stroke marine engines emit waste heat in higher temperatures, the efficiency is reduced when integrated with WHR systems. Therefore, in literature studies, it was observed that two-stroke engines provide higher WHR values than four-stroke engines.

3.2. Results and Discussions about Thermodynamic Cycle Types

With the help of WHR systems, it is aimed to obtain usable energy from heat energy while providing heat recovery. For this purpose, WHR systems can benefit from different thermodynamic cycles. The most preferred thermodynamic cycles are ORC, RC, KC, and SC. However, literature studies haven't specific findings of KC. Therefore, Mirolli [39] researched the WHR system design for a cement plant. As a result of this research, it has been concluded that KC in the cement plant is 40% more efficient than the RC for temperature values between 200 °C and 400 °C obtained from marine diesel engines.

On the other hand, Ulrik Larsen et al. [14] have concluded that the use of ORC on a two-stroke diesel engine is more efficient than the use of KC and SC. These different findings show us we need more data on this area. For this reason, we need new studies to compare thermodynamic cycles and make more specific results. But at the same time, literature studies have some consensus on thermodynamic cycles. The literature studies show us that the use of KC is more successful in all motor load operations.

On the other hand, the use of RC shows that it has higher recovery efficiency and is a safe-reliable technology. Although combined-cycle systems are not widely used, it has significant potential to achieve higher thermal efficiency and mitigate the problem of atmospheric pollution. It is noteworthy that literature studies about combined cycles are necessary for the future in this context.

3.3. Results and Discussions about Parts Used as Heat Sources

The waste heat sources in the marine industry generally have tremendous amounts of waste energy and perpetual supply. And these are two significant reasons why waste heat recovery systems are essential in the marine industry. Usually, there are three recoverable waste heat sources in the marine industry: jacket water, air cooler, and exhaust gas. The jacket water temperature is between 70 and 120 °C, the air cooler temperature is between 130 and 150 °C, and the exhaust gas temperature is between 250 and 500 °C.

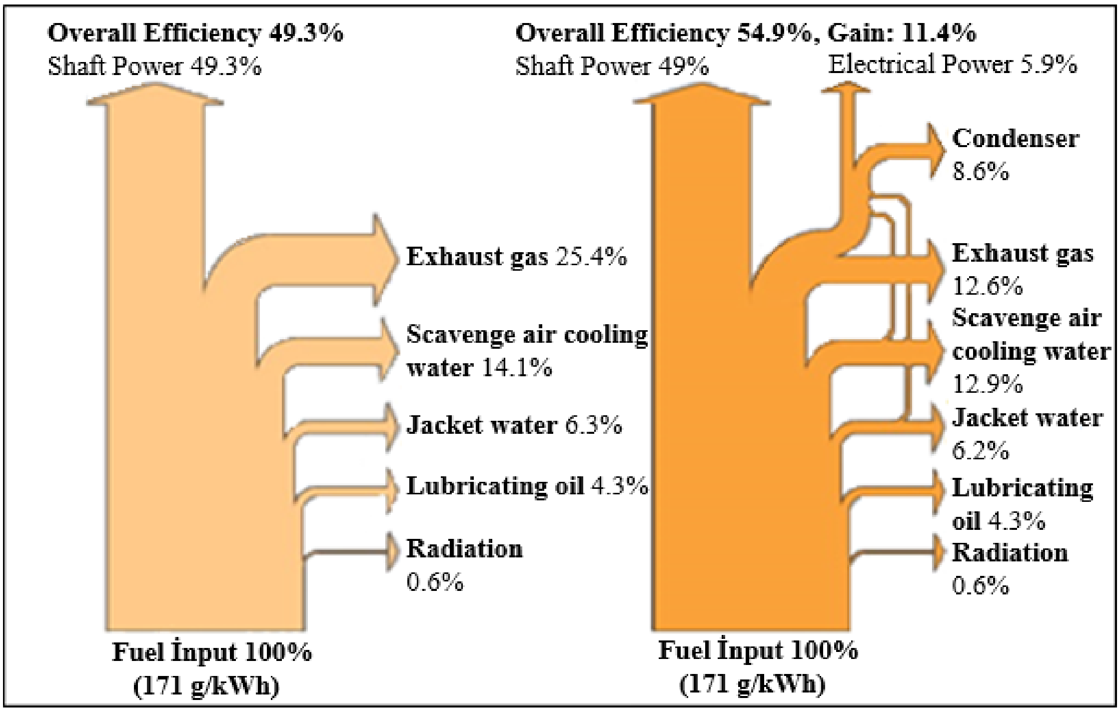


Figure 9. Energy values and fuel consumption variation in engines with and without WHR [40].

The literature studies show us that the exhaust gas from the engine is the best quality, efficient and sustainable waste heat source for WHR systems used in the marine industries. Therefore, many of the WHR systems used in the marine industry have aimed to utilize exhaust gas waste heat. As shown in Figure 9, the Wartsila-Sulzer RTA96-C engine with a combined WHR system has a specific fuel consumption of 4.6% less than the engine without this system. Furthermore, the propulsion efficiency of the combined system increased from 49.3% to 54.9%, corresponding to a gain of around 11.4%. In Figure 9, In figure 9, energy wastes in a marine engine and the progress achieved with a heat recovery system are schematized [36].

3.4. Results and Discussions about Working Fluid

In WHR systems used in the marine industries, it is vital to evaluate even low-temperature waste heat. Therefore, a working fluid that can operate at low temperature and pressure levels should be determined. The WHR technology, which includes the ORC system, is considered promising to achieve this demand. ORC systems can provide high efficiencies in motors with a running time of 8000 hours or more per year. With this purpose, the fluid to be selected as the working fluid is tolerant to temperature and pressure variation. In addition, it is desired that the working fluid be non-flammable, non-explosive, non-toxic, and environmentally friendly. Besides all this, the flashpoint of the working fluid must be higher than the engine room temperature. Otherwise, it is necessary to take extra precautions in this situation. R245fa, R134, and n-Heptane fluids are good candidates for use in up-to-date ORC systems. In Figure 10, the power input differences of LNG-based cooling and sea water-based cooling systems in two different engine types (6L34DF and 6L20DF) and different loading rates are schematized [18].

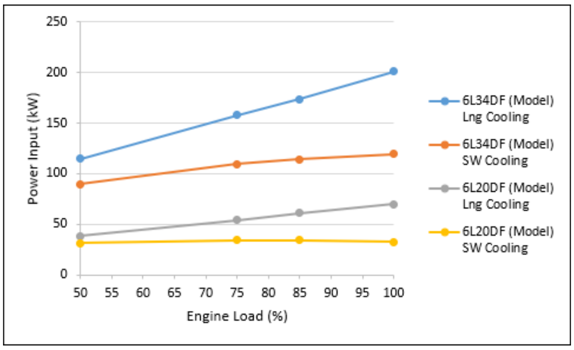


Figure 10. Power savings at different engine models for different engine loads.

3.5. Results and Discussions about Relationship between WHR Systems and Emission Rates

According to statistical data, approximately 2.8% of global greenhouse gas emissions of an average of 1 billion tons are emitted annually from maritime transport. In this context, it is essential to ensure that the emissions from the exhaust gas in the marine industries are eliminated and comply with IMO standards. Therefore, the efficiency and emission removal performance of the WHR technologies to be integrated into the system should be evaluated completely. It should also be noted that when the WHR system is used, fuel consumption will be reduced and, therefore, a direct reduction in the amount of emissions released into the atmosphere. In addition, a selective catalytic reactor, exhaust gas recirculation unit, and pre-scrubber can be integrated into the WHR system to achieve more high emission reduction at the exhaust gas. The literature studies showed us that a large volume container ship could reduce the emissions up to 1000 tons per year when using an efficient WHR system.

4. Conclusions

In this study, the assesment and comparison of Waste Heat Recovery (WHR) systems in maritime industries are detailed in energy, environment, and economy. WHRs are assessed according to the following properties; type and stroke of the engine, thermodynamic cycle, waste heat source, working fluids, rates of emissions-reducing, and potential economic gains for all of these modifications.

With this research, WHR systems are compared in terms of energy, environment, and economy to help determine the optimum system. In addition, while the systems were examined, the first investment and depreciation periods were stated, and information was given about the payback period of WHR systems. Finally, the primary deficiencies in the literature are mentioned, and research areas and subjects should be focused on in the future. As a result, using an efficient WHR system in the marine industry can provide substantial energy recovery. Furthermore, operating costs can be reduced with WHR systems. Thus, a significant reduction in emission rates can be achieved in addition to energy recovery.

References

1. Kayabasi, E., and Kurt, H., Simulation of Heat Exchangers and Heat Exchanger Networks with an Economic Aspect, Engineering Science and Technology, An International Journal'21, **2018,** 21(1):70-76.
2. WTO, World Trade Statistical Review 2019, World Trade Organization, Geneva, Switzerland, **2019**.
3. UNCTAD, Review of Maritime Transport, United Nations Conference on Trade and Development, **2019**, October.
4. Uysal, F., and Sagiroglu, S., The Effects of a Pneumatic-Driven Variable Valve Timing Mechanism on the Performance of an Otto Engine, Journal of Mechanical Engineering, **2015**, 61(11):632-640
5. Endresen, Ø., and Sørgard, E., Emission from International Sea Transportation and Environmental Impact, J. Geophys. Res. D Atmos., **2003**, 108(17).
6. IMO, Ships Face Lower Sulphur Fuel Requirements in Emission Control Areas, International Maritime Organization, **2015**, January.
7. Barret, C., An Analysis of the IMO 2020 Sulphur Limit, İEA, **2018**.
8. Oikawa, K., Yongsiri, C., Takeda, K., and Harimoto, T., Seawater Flue Gas Desulfurization: It's Technical Implications and Performance Results, Environ. Prog., **2003**, 22(1):67:73.
9. Stavrakaki, A., Jonge, E. D., Hugi, C., Whall, C., Minchin, W., Ritchie, A., and McIntyre, A., Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments, European Commission Directorate General Environment, **2015**, August.
10. Ozcan, H., and Kayabasi, E., Thermodynamic and Economic Analysis of a Synthetic Fuel Production Plant via CO2 Hydrogenation Using Waste Heat from an Iron-Steel Facility, Energy Conversion and Management, **2021**, May:114074.
11. Baldi, F., and Gabrielii, C., A Feasibility Analysis of Waste Heat Recovery Systems for Marine Applications, Energy, **2015**, 80:654-665.
12. MAN Diesel and Turbo, Thermo Efficiency System (TES)—for Reduction of Fuel Consumption and CO2 Emission, MAN B&W Diesel A/S: Copenhagen, Denmark, 2014, October.
13. Karslen, B. H., Rules for Ships, GL DNV, **2020**.
14. Larsen, U., Sigthorsson, O., and Haglind, F., A Comparison of Advanced Heat Recovery Power Cycles ın a Combined Cycle for Large Ships, Energy, **2014**, 74:260-268.
15. Singh, D. V., and Pedersen, E., A Review of Waste Heat Recovery Technologies for Maritime Applications, Energy Convers, **2016**, 111:315-328.
16. Yu, Z., Liang, Y., and Li, W., A Waste Heat-Driven Cooling System Based on Combined Organic Rankine and Vapour Compression Refrigeration Cycles, Appl. Sci., **2019**, 9(20).
17. Bellolio, S., Lemort, V., and Rigo, P., Organic Rankine Cycle Systems for

Waste Heat Recovery in Marine Applications, SCC Int. Conf. Shipp. Chang. Clim., **2015**.

18. Pallis, P., Varvagiannis, E., Braimakis, K., Roumpedakis, T., Leontaritis, A. D., and Karellas, S., Development, Experimental Testing and Techno-Economic Assessment of a Fully Automated Marine Organic Rankine Cycle Prototype for Jacket Cooling Water Heat Recovery, Energy, **2021**, 228(August):120596.
19. Salmi, W., Vanttola, J., Elg, M., Kuosa, M., and Lahdelma, R., Using Waste Heat of Ship as Energy Source for an Absorption Refrigeration System, Applied Thermal Engineering, **2017**, 115(March):501-516
20. Cao, T., Lee, H., Hwang, Y., Radermacher, R., and Chun, H., Performance Investigation of Engine Waste Heat Powered Absorption Cycle Cooling System for Shipboard Applications, Appl. Therm. Eng., **2015**, 90:820-830.
21. Ng, C. W., Tam, I. C. K., and Wu, D., System Modelling of Organic Rankine Cycle for Waste Energy Recovery System in Marine Applications, Energy Procedia, **2019**, 158:1955-1961.
22. Baldasso, E., Andreasen, J. G., Mondejar, M. E., Larsen, U., and Haglind, F., Technical and Economic Feasibility of Organic Rankine Cycle-Based Waste Heat Recovery Systems on Feeder Ships: Impact of Nitrogen Oxides Emission Abatement Technologies, Energy Convers. Manag., **2019**, 183:577-589.
23. Song, J., Thermodynamic Analysis and Performance Optimization of an Organic Rankine Cycle (Orc) Waste Heat Recovery System for Marine Diesel Engines, Energy, **2015**, 82:976-985.
24. Larsen, U., System Analysis and Optimisation of a Kalina Split-Cycle for Waste Heat Recovery on Large Marine Diesel Engines, Energy, **2014**, 64:484-494.
25. Shu, G., Liang, Y., Wei, H., Tian, H., Zhao, J., and Liu, L., A Review of Waste Heat Recovery on Two-Stroke IC Engine Aboard Ships, Renew. Sustain. Energy Rev., **2013**, 19:385-401.
26. Jong, J. Y., Rim, C. H., Choi, M. S., and Om, H. C., Comprehensive Evaluation of Marine Waste Heat Recovery Technologies Based on Hierarchy-Grey Correlation Analysis, Journal of Ocean Engineering and Science, **2019**, 4(4):308-316.
27. Wärtsilä, Marine and Oil & Gas Markets Table of Contents, Online Wärtsilä Encyclopedia, **2016**.
28. Kuiken, K., The Diesel Engines: for Ship Propulsion and Power Plants. Onnen: Target Global Energy Training. **2008**.
29. Theotokatos, G., and Livanos, G., Techno-Economical Analysis of Single Pressure Exhaust Gas Waste Heat Recovery Systems in Marine Propulsion Plants, Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ., **2013**, 227(2):83-97.
30. Nielsen, R. F., Haglind, F., and Larsen, U., Design and Modeling of an Advanced Marine Machinery System Including Waste Heat Recovery and Removal of Sulphur Oxides, Energy Convers. Manag., **2014**, 85:687-693.
31. Cheng, Z., Wang, Y., Sun, Q., Wang, J., Zhao, P., and Dai, Y., Thermodynamic Analysis of a Novel Ammonia-Water Cogeneration System for Maritime Diesel Engines, ASME Turbo Expo 2020: Turbomachinery Technical Conference and Exposition, **2021**, January.
32. Sakalis, G., Investigation of Supercritical CO2 Cycles Potential for Marine Diesel Engine Waste Heat Recovery Applications, Applied Thermal Engineering, **2021**, 195:117201.

33. Cao, T., Lee, H., Hwang, Y., Radermacher, R., and Chun, H. H., Modeling of Waste Heat Powered Energy System for Container Ships, Energy, **2016**, 106:408-421.
34. Vélez, F., Segovia, J. J., Martín, M. C., G. Antolín, Chejne, F., and Quijano A., A Technical, Economical and Market Review of Organic Rankine Cycles for The Conversion Of Low-Grade Heat for Power Generation, Renew. Sustain. Energy Rev., **2012**, 16(6):4175-4189.
35. Bashan, V., and Kokkulunk, G., Exergoeconomic and Air Emission Analyses for Marine Refrigeration with Waste Heat Recovery System: A Case Study, Journal of Marine Engineering & Technology, **2020**, 19:3.
36. Kyriakidis, F., Sørensen, K., Singh, S., and Condra, T., Modeling and Optimization of Integrated Exhaust Gas Recirculation and Multi-Stage Waste Heat Recovery in Marine Engines, Energy Convers. Manag., **2017**, 151(March):286-295.
37. Suárez, S. F., Roberge, D., and Greig, A. R., Safety and CO2 Emissions: Implications of Using Organic Fluids in a Ship's Waste Heat Recovery System, Mar. Policy, **2017**, 75:191-203.
38. Ouyang, T., Su, Z., Wang, F., Jing, B., Huang, H., and Wei, Q., Efficient and Sustainable Design for Demand-Supply and Deployment of Waste Heat and Cold Energy Recovery in Marine Natural Gas Engines, Journal of Cleaner Production, **2020**, 274(20): 123004.
39. Mirolli, M. D., Ammonia-Water Based Thermal Conversion Technology: Applications in Waste Heat Recovery for The Cement Industry, IEEE Cem. Ind. Tech. Conf. Rec., **2007**, 234-241.
40. Babicz, J., Ship Technology, HELSINKI: Wärtsilä Encyclopedia, **2015**.