Journal of Marine Science and Engineering

MDPI

Article

Thermodynamic Analysis of a Marine Diesel Engine Waste Heat-Assisted Cogeneration Power Plant Modified with Regeneration Onboard a Ship

Haydar Kepekci [1,*] and Cuneyt Ezgi [2]

1 Department of Mechatronics Engineering, Istanbul Gelişim University, Istanbul 34310, Turkey
2 Department of Marine Engineering, Piri Reis University, Istanbul 34940, Turkey; cezgi@pirireis.edu.tr
* Correspondence: hikepekci@gelisim.edu.tr; Tel.: +90-5394538347

Abstract: The objective of this study is to perform a thermodynamic analysis on a marine diesel engine waste heat-assisted cogeneration power plant modified with regeneration onboard a ship. The proposed system utilizes the waste heat from the main engine jacket water and exhaust gases to generate electricity and heat, thereby reducing the fuel consumption and CO_2 emissions. The methodology includes varying different turbine inlet pressures, extraction pressures, and fractions of steam extracted from the turbine to evaluate their effects on the efficiency, utilization factor, transformation energy equivalent factor, process heat rate, electrical power output, saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions. The analysis demonstrates that the proposed system can achieve an efficiency of 48.18% and utilization factor of 86.36%, savings of up to 57.325 kg/h in fuel, 65.606 USD/h in fuel costs, and 180.576 kg/h in CO_2 emissions per unit mass flow rate through a steam turbine onboard a ship.

Keywords: ship; cogeneration; waste heat; engine

check for updates

Citation: Kepekci, H.; Ezgi, C. Thermodynamic Analysis of a Marine Diesel Engine Waste Heat-Assisted Cogeneration Power Plant Modified with Regeneration Onboard a Ship. *J. Mar. Sci. Eng.* **2024**, *12*, 1667. https://doi.org/10.3390/jmse12091667

Academic Editor: Decheng Wan

Received: 21 August 2024
Revised: 12 September 2024
Accepted: 16 September 2024
Published: 18 September 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Ships are versatile vessels used for a variety of purposes. One of the most common uses is freight transport. Cargo ships enable the transportation of large amounts of material by sea and are a key part of global trade [1]. Sea transportation is a more economical option compared to land or air transportation. This makes it more often the preferred option, especially over long distances. Cargo ships are an important part of international trade, allowing large amounts of material to be transported safely between different countries and continents. Advanced technologies and equipment enable the safe and efficient transportation of cargo, minimizing the risks that may occur during the transportation process. These features make cargo ships an important component of global trade and economic activities [2]. Approximately 90% of the world's transportation is carried out by ships. Many fossil fuels, which are harmful to the environment and human health, are consumed in the main engines that propel the vessels and the generators that produce electricity and heat. The high number of ships at sea, increasing energy costs, global warming problems, and International Maritime Organization (IMO) regulations on energy efficiency in ships necessitate efficient and sustainable system designs onboard ships. One of the solutions that will provide energy efficiency onboard ships is a marine diesel engine waste heat-assisted cogeneration power plant modified with regeneration.

The energy consumption of cargo ships is large and varies depending on various factors. Large and heavy cargo ships consume significant amounts of energy due to their large capacity and long distances. These ships usually use large diesel engines, which results in high fuel consumption [3]. The speed of ships also affects energy consumption. Higher speeds lead to more drag and therefore more energy consumption. Loading and unloading processes also affect energy consumption because the type and distribution of cargo change the ship's stability and drag characteristics. In recent years, various technological innovations and studies on alternative fuels have been carried out to increase the energy efficiency. These innovations are important steps toward reducing the energy consumption of cargo ships and minimizing environmental impacts [4]. The maritime industry significantly contributes to global greenhouse gas emissions due to the extensive use of marine diesel engines, which consume substantial amounts of fossil fuels. The increasing fuel costs and stringent International Maritime Organization (IMO) regulations mandate a reduction in CO_2 emissions and an improvement in energy efficiency. However, c the current systems onboard ships are not optimized to recover waste heat effectively, leading to inefficiencies in fuel usage and higher operational costs. This study addresses the problem by proposing a modified waste heat-assisted cogeneration power plant to enhance energy efficiency and reduce fuel consumption and emissions on ships.

In addition to costs, high amounts of fuel consumption also have environmental impacts. Cargo ships usually obtain their energy through diesel engines. These engines constitute the main power source of the ship and consume large amounts of fuel. Diesel engines are used to drive the ships' main engines and generators. The most used type of fuel is low-quality and high-viscosity diesel fuel known as bunker fuel. Although this fuel is lower in cost, it contains high amounts of sulfur and carbon [5]. The energy consumption of ships has various negative impacts on the environment. The emissions from diesel engines include harmful gases such as carbon dioxide (CO_2), nitrogen oxides (NO_x), and sulfur dioxide (SO_2). These emissions damage marine ecosystems by increasing air pollution and the acidification of seawater. In addition, waste and marine pollution originating from ships, especially leaks of marine fuels and other chemical wastes, negatively affect marine life and the marine environment. To reduce all these negative situations, revisions to be made to engines to reduce the amount of fuel used in ships are of great importance [6].

There are various ways to increase the energy efficiency of ships. The most researched method recently is energy production from waste heat. Waste heat on ships usually comes from various sources such as engines, generators, power transmission systems, cooling systems, and exhaust gases. The main diesel engines and electric generators produce a large amount of heat while operating, and this heat is usually removed through cooling systems. High-temperature gases from engine exhaust systems are also a significant source of waste heat. In addition, power transmission systems and cooling systems also produce heat while operating, and this heat accumulates in the ship's interior. The effective management of this waste heat is critical to increasing energy efficiency and reducing fuel consumption. Advanced heat recovery systems help to meet the ship's energy needs by reusing this waste heat. In this way, both operational costs and environmental impacts are reduced [7]. In waste heat energy production, systems such as the Rankine cycle are generally used. These systems convert some of the waste heat into electrical energy by vaporizing it with a turbine. In addition, some modern ships use advanced technologies such as thermal electric generators and organic Rankine cycles [8]. These technologies help meet the ship's energy needs while also reducing environmental impacts and operational costs. Waste heat recovery systems allow ship engines to operate at a lower load, which reduces fuel consumption [9].

Examples of systems used to increase energy efficiency and reduce energy costs on ships include cogeneration and trigeneration [10,11]. Cogeneration is a system that aims to produce both electricity and heat from the same energy source. In this system, an energy source (usually natural gas or diesel) produces electricity using a turbine or engine, and the waste heat generated in this process is usually recovered through a heat exchanger or steam system. This waste heat is used for heating and hot water production on board [12,13]. Trigeneration aims to provide cooling as well as electricity and heat production in addition to the cogeneration system. In this system, electricity is usually produced using a turbine or engine, and waste heat is used for heating by a steam generator or heat exchanger [14]. In addition, cooling is achieved from this waste heat with the help of an absorption cooling unit [15]. Trigeneration systems on ships both increase the energy efficiency and meet cooling needs. It is especially useful when various systems inside the ship need to be cooled. For this reason, the trigeneration system is quite advantageous and superior to cogeneration [16].

Recently, systems designed to produce energy from the waste heat of ships have become increasingly widespread. Some of the studies in the literature on this subject are as follows. Tien et al. proposed a methodology that analyzes the performance of cogeneration systems used on ships and examines the factors affecting the performance of the system. They numerically examined the relationship between the seawater used as engine coolant and the exhaust gas temperatures and confirmed their work experimentally. As a result, they found that the power consumption of the pump circulating the working fluid is inversely proportional to the boiler outlet temperature. They also found that the efficiency of the cogeneration system increases as the exhaust outlet temperature decreases [17]. Liang and his colleagues proposed a cogeneration system that aims to produce electricity from the waste heat of engine cooling water and exhaust gases used in ships. They examined the system they created by combining the Rankine cycle and absorption refrigeration cycle. They found that this combined cycle, which can be used in ships, significantly increased the exergy efficiency. They obtained the exergy value as a maximum of 4.65 MW at 300 kPa evaporation pressure. This value shows that the exergy efficiency of the system they designed increased by 12% compared to the Rankine cycle [18]. Wang et al. numerically investigated the parameters affecting the efficiency of a ship's power plant cogeneration cycle. They designed a system using a recovery cycle that converts engine and exhaust gas energy into mechanical work. They focused on the effect of the turbine power on the efficiency in their calculations. They used LNG as fuel in the cogeneration system. As a result, they found that the effect of the heat exchangers used in the cogeneration system on efficiency did not exceed 10% and the system efficiency decreased by 5–6% with the increase in the inlet temperature of the fluid to the compressor [19]. Brozičević and his colleagues investigated the applications of combined heat and power (CHP) systems on ships and performed an economic analysis of these systems. They also compared different cogeneration systems on ships and proposed the most suitable models for various ship types [20]. Liang and his colleagues designed a cogeneration system that produces electricity and cooling energy using the exhaust heat of ship engines and theoretically examined its performance. They combined the Rankine cycle (RC) and absorption cooling cycle (ARC) in their designed system. While the working fluid of the Rankine cycle was water in the system, they selected the working fluid for the ARC as an ammonia–water mixture. As a result of their investigations, they found that the energy efficiency of the designed system was much higher at low condensing temperatures compared to the basic Rankine cycle. They found that when the condensing temperature was 323 K, the exergy efficiency of the combined power system increased by 84% [21].

Liua et al. designed a new cogeneration system that converts the waste heat of exhaust gas and the jacket cooling water of marine engines into electricity and cooling energy. This system aims to effectively utilize high-, medium-, and low-temperature heat sources by combining the Rankine cycle (RC), organic Rankine cycle (ORC), and absorption cooling cycle (ARC). They found that this system can produce 7620 kW of electricity and 2940 kW of cooling energy under nominal operating conditions. With the system they designed, the thermal efficiency of the engine increased by about 10%, while the exergy efficiency increased by 5.3% and 7.3% compared to RC and ORC systems, respectively [22].

Qu et al. designed and tested a high-efficiency waste heat recovery system consisting of a steam Rankine cycle (RC), organic Rankine cycle (ORC), and power turbine (PT) to recover the exhaust and jacket water heat of low-speed diesel engines for ships. With this system designed to increase the energy efficiency in line with global decarbonization targets, they aimed to reduce carbon emissions by recovering the engine's waste heat. When they tested the system they designed, they saw that it could produce 1079.1 kW of power at 100% load. The maximum exergy efficiency was calculated as 65.72%. In addition, the payback period of this system was calculated as 5.2 years and the depreciation payback period as 6.9 years [23]. Ouyang et al. proposed a system developed to reduce fossil fuel consumption and increase energy efficiency by recovering waste heat from marine engines. Unlike known methods in the literature, they designed two evaporators for the organic Rankine cycle (ORC) in their study and used the heat obtained from the condenser to maintain an absorption cooling system to meet the cooling requirements. They calculated the thermal efficiency of this system as 16.22% and the exergy efficiency as 48.25%. They also found that materials with high specific heat are more compatible with cooling targets [24]. Qun et al. investigated waste heat recovery (WHR), which is one of the most effective methods to increase the efficiency of internal combustion engines. They proposed an electricity–cooling cogeneration system (ECCS) based on the Rankine–absorption cooling combination cycle for liquid fuel engines. With this proposed system, they aimed to increase the overall efficiency of the WHR system by preventing the heat in the condenser from being wasted. However, they found that the condensation temperature of the Rankine cycle (RC) had to be increased to use the absorption cooling system, and they stated that this would lead to a decrease in the output power of the RC. In this study, they examined in detail the relationship between the gain of the absorption cooling system and the loss of the RC in the system they designed [25].

To lessen the impact of shipping on climate change, the International Maritime Organization (IMO) began considering technical and operational solutions to increase ship energy efficiency in the early 2000s. In 2011, the IMO amended MARPOL Annex VI to require technical and operational energy efficiency measures to limit the quantity of CO_2 emissions from international shipping. The Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) went into effect on January 1, 2013. These policies are the first global mandated GHG-reduction regime for an international industry sector, and they have been driving energy efficiency improvements throughout the global fleet for more than a decade. Goal-based and technology-neutral laws encourage the deployment of energy-efficient technologies such as hull air lubrication, wind-aided propulsion, and waste heat recovery. IMO Member States adopted further energy efficiency measures in 2021 to lower international shipping's carbon intensity by at least 40% by 2030 compared to 2008. Continuous increases in shipping's energy efficiency are critical and will help to offset the higher cost of alternative low- and zero-carbon fuel sources [26].

In this study, a cogeneration power plant assisted with engine waste heat for ships is designed, and its thermodynamic analysis is performed. This study investigates the effects of different turbine inlet pressures, extraction pressures, and fractions of steam extracted from the turbine on various performance metrics, including the efficiency, utilization factor, process heat rate, electrical power output, saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions. The Engineering Equations Solver (EES) software (version 11.898) is employed to obtain the thermophysical properties of the working fluid, such as the enthalpy and entropy, and to conduct a comprehensive analysis of the cogeneration power plant. EES is chosen for its robust capabilities in managing thermodynamic properties and solving complex engineering equations simultaneously. Additionally, custom codes are developed within EES to model different scenarios by varying parameters like the turbine inlet pressure, extraction pressure, and the fraction of steam extracted from the turbine, enabling a detailed system performance analysis under different operational conditions and ensuring accurate and reliable results. The input data can be seen in Appendix A.

2. Case Study

The system includes an engine jacket water heat exchanger, an exhaust gas waste heat boiler, a boiler, a turbine, a generator, a condenser, a process heater, a feedwater heater, and a seawater-cooled condenser. It also includes a mixture tank and two pumps. The water heated by the energy transferred from the engine jacket water is given to the boiler. Its temperature is increased in the exhaust gas waste heat boiler. The water evaporated in the boiler is sent to the turbine and electricity is produced with a generator connected to the turbine. The high-pressure steam coming out of the turbine is sent to the process heater and feedwater heater. The low-pressure steam at the turbine exit is condensed in the seawater-cooled condenser, and the cooled water is sent back to the pump. The boiler inlet water is preheated in the system using engine jacket water and exhaust gas waste heat. The design of marine engine waste heat-assisted cogeneration power plant modified with regeneration onboard a ship is illustrated in Figure 1.

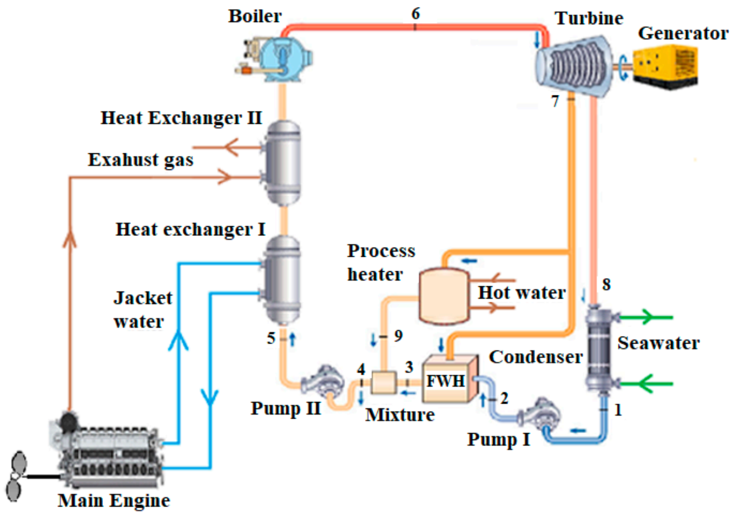

Figure 1. System design onboard ship.

The T–s diagram of the design is illustrated in Figure 2. In this study, the turbine inlet pressure, extract pressure, and a fraction of steam extracted from the turbine for the feedwater heater and process heater are varied.

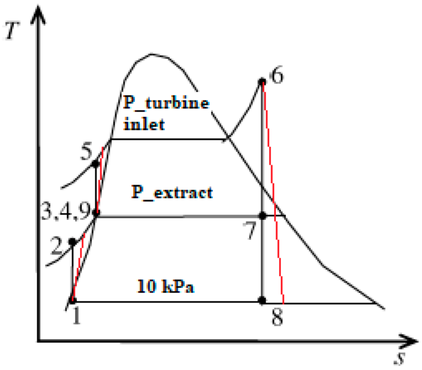

Figure 2. T–s diagram of system.

The calculations are made for turbine inlet pressures of 5000, 6000, 7000, 8000, 9000, and 10,000 kPa because the electrical power obtained at these pressures will eliminate the need for a diesel generator onboard the ship. In this study, extraction pressures from the turbine are chosen between 500 and 2000 kPa because the process heat on ships is usually provided by steam at a pressure of at least 500 kPa. Therefore, pressures below 500 kPa are not considered.

The engine characteristics, particularly the power output and specific consumption, are provided in Tables 1–3.

Table 1. Technical data for marine diesel engine.

Engine output (kW/HP)	520/710
Engine speed (rpm)	720
Number of cylinders	4
Cylinder bore (mm)	200
Stroke (mm)	280
Compression ratio	15

Table 2. Operating data for marine diesel engine.

Parameters	Engine Load (100%)	(85%)	(75%)	(50%)
Exhaust gas flow (kg/s)	0.97	0.84	0.76	0.55
Exhaust gas temperature after turbo charger (°C)	360	360	360	370
Specific fuel consumption (g/kWh)	194	195	197	204

Table 3. Heat balance at full load for marine diesel engine.

Type of Waste Heat	Rate of Heat Transfer (kW)
Charge air	157
Lubricating oil	67
Exhaust gases	356
Radiation	31
Jacket water	127

3. Governing Equations

To analyze the proposed solution effectively, the following governing equations [27] are used to model the thermodynamic performance of the waste heat-assisted cogeneration system onboard ships.

Assumptions

1. Steady operating exists.
2. Kinetic and potential energy changes are negligible.
3. Pressure drops and heat losses in piping are negligible.
4. The pump efficiency is 0.85.
5. The turbine efficiency is 0.85.
6. The generator efficiency is 0.95.
7. The condenser pressure is 10 kPa.
8. The turbine inlet temperature is 350 °C.
9. The turbine inlet mass flow rate is 1 kg/s.
10. The engine's fuel is marine diesel oil (MDO).
11. The pinch point temperature difference is 10 °C between cold and hot fluids in the heat exchangers and condenser.

The mass balance equation for a general steady flow system is expressed as

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \tag{1}$$

The energy balance equation for a general steady flow system is expressed as

$$\dot{E}_{in} = \dot{E}_{out} \tag{2}$$

$$\dot{Q} - \dot{W} = \sum_{out} \dot{m}\left(h + \frac{V^2}{2} + gz\right) - \sum_{out} \dot{m}\left(h + \frac{V^2}{2} + gz\right) \tag{3}$$

The rate of heat transfer from the exhaust gas is expressed as

$$\dot{Q}_{exh} = \dot{m}_c.c_{p,c}.(T_{c,out} - T_{c,in}) = \dot{m}_h.c_{p,h}.(T_{h,in} - T_{h,out}) \tag{4}$$

$T_{h,out-}T_{c,in} \geq \Delta T_{pinch}$ is the minimum temperature difference required at the closest point between the hot and cold streams.

The pump:

$$\text{Mass balance}: \ \dot{m}_{in} = \dot{m}_{out} \tag{5}$$

$$\text{Energy balance}: \ \dot{m}_{in}h_{in} + \dot{W}_p = \dot{m}_{out}h_{out} \tag{6}$$

The steam turbine:

$$\text{Mass balance}: \ \dot{m}_{in} = \dot{m}_{out} \tag{7}$$

$$\text{Energy balance}: \ \dot{m}_{in}h_{in} = \dot{m}_{out}h_{out} + \dot{W}_t \tag{8}$$

The condenser:

$$\text{Mass balance}: \ \dot{m}_{in} = \dot{m}_{out} \tag{9}$$

$$\text{Energy balance}: \ \dot{m}_{in}h_{in} = \dot{m}_{out}h_{out} + \dot{Q}_{cond} \tag{10}$$

The mixture tank:

$$\text{Mass balance}: \ \dot{m}_3 + \dot{m}_9 = \dot{m}_4 \tag{11}$$

$$\text{Energy balance}: \ \dot{m}_3h_3 + \dot{m}_9h_9 = \dot{m}_4h_4 \tag{12}$$

The thermal efficiency of the cogeneration is determined from the following:

$$\eta_{th} = \frac{w_{net}}{q_{in}} \tag{13}$$

The utilization factor is calculated as

$$\epsilon_u = \frac{Net\ power\ output\ +\ Process\ heat\ delivered}{Total\ heat\ input} = \frac{\dot{W}_{net}\ +\ \dot{Q}_p}{\dot{Q}_{in}} \tag{14}$$

The power and thermal energy ratio (Ψ) [20] is

$$\Psi = \frac{\dot{W}_{elect}}{\dot{Q}_{process}} \tag{15}$$

The transformation energy equivalent factor (F_{TEE}) [20] is

$$F_{TEE} = \frac{\left(\dot{Q}_{in} - \frac{\dot{Q}_{process}}{\eta_{boiler}}\right)}{\dot{W}_{elect}} \tag{16}$$

The transformation energy equivalent factor (F_{TEE}) considers the consumed fuel energy reduction when compared to the consumption of fuel energy used for thermal energy production only.

Following the establishment of the governing equations, the calculation methodology for fuel savings, costs, and emissions is detailed to provide a comprehensive understanding of the analysis. The calculations for fuel savings, cost reductions, and emissions reductions are based on specific formulas and assumptions related to engine performance and operational conditions.

The saved marine diesel fuel consumption (SFC) can be calculated as

$$SFC = \frac{\dot{Q}_{saved}}{H_u.\eta_{boiler}} \tag{17}$$

The cost savings can be calculated as

$$\text{Cost Savings (USD/h)} = \text{Fuel Savings (kg/h)} \times \text{Fuel Cost (USD/kg)}$$

In this study, the fuel cost for MDO is $4.12/gallon, which is the value in 2024.

The emissions reduction is calculated based on the decrease in fuel consumption and the emission factors for carbon dioxide (CO_2) emissions, which are specific to the type of fuel used (marine diesel fuel, MDO). The CO_2 emission factor for MDO is 3.15 kg CO_2/kg fuel. The emissions reduction can be calculated as

$$CO_2 \text{ Emissions Reduction (kg/h)} = \text{Fuel Savings (kg/h)} \times \text{Emission Factor (kg } CO_2\text{/kg fuel)}$$

4. Results

The calculations are performed for a constant condenser pressure of 10 kPa because the maximum seawater inlet temperature through the condenser is 32 °C, according to Turk Loydu's rules [28].

For a turbine inlet pressure of 5000 kPa, the effect of the extraction pressure and fraction of steam extracted from the turbine to be used for the process and that of the feedwater heater on the efficiency and utilization factor are illustrated in Figure 3.

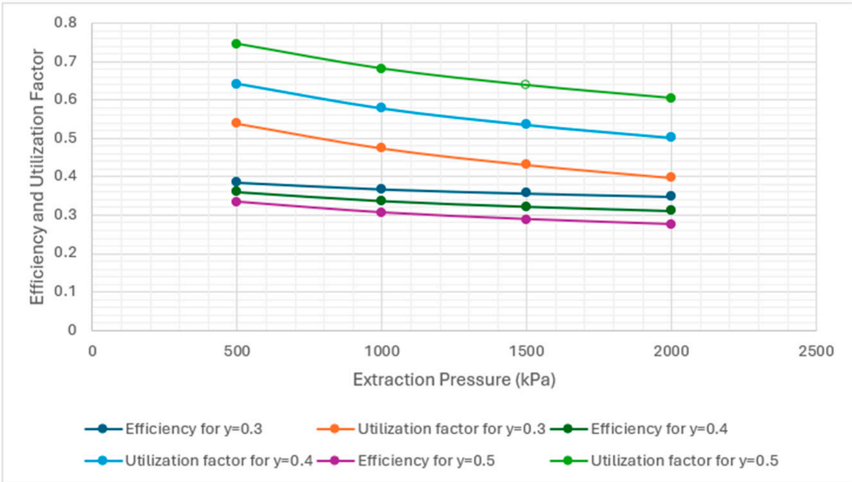

Figure 3. Efficiency and utilization factor versus extraction pressure for turbine inlet pressure of 5000 kPa.

As seen in Figure 3, as the extraction pressure from the turbine increases, the utilization factor and thermal efficiency decrease. As the fraction of steam extracted from the turbine increases, the utilization factor increases but the thermal efficiency decreases. For an extraction pressure of 500 kPa, y = 0.5, and the thermal efficiency and utilization factor are 0.334 and 0.745, respectively. For an extraction pressure of 2000 kPa, y = 0.5, and the thermal efficiency and utilization factor are 0.275 and 0.605, respectively. For an extraction pressure of 500 kPa, y = 0.3, the thermal efficiency and utilization factor are 0.385 and 0.538, respectively. For an extraction pressure of 2000 kPa, y = 0.3, and the thermal efficiency and utilization factor are 0.348 and 0.397, respectively. The thermal efficiency and utilization factors are inversely proportional at the same extraction pressure of the turbine.

For a turbine inlet pressure of 5000 kPa, the effect of the extraction pressure and fraction of steam extracted from the turbine to be used for the process and that of the feedwater heater on the process heat rate and electrical power are illustrated in Figure 4.

As seen in Figure 4, as the extraction pressure from the turbine increases, the process heat rate and electrical power decrease. As the fraction of steam extracted from the turbine increases, the process heat rate increases but the electrical power decreases. For an extraction pressure of 500 kPa, y = 0.5, and the process heat rate and electrical power are 787.2 kW and 609.045 kW, respectively. For an extraction pressure of 2000 kPa, y = 0.5, and the process heat rate and electrical power are 631.4 kW and 501.315 kW, respectively. For an extraction pressure of 500 kPa, y = 0.3, and the process heat rate and electrical power are 293.3 kW and 700.435 kW, respectively. For an extraction pressure of 2000 kPa, y = 0.3, and the process heat rate and electrical power are 93.29 kW and 633.935 kW, respectively. The process heat rate and electrical power are inversely proportional at the same extraction pressure of the turbine.

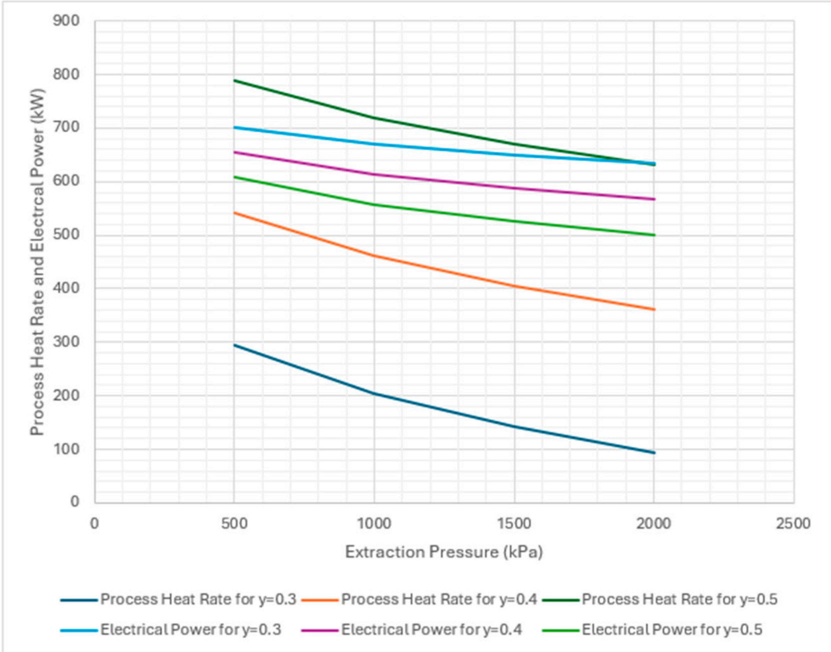

Figure 4. Process heat rate and electrical power versus extraction pressure for turbine inlet pressure of 5000 kPa.

For a turbine inlet pressure of 5000 kPa, the effect of the extraction pressure and fraction of steam extracted from the turbine to be used for the process and that of the feedwater heater on the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions are illustrated in Figure 5.

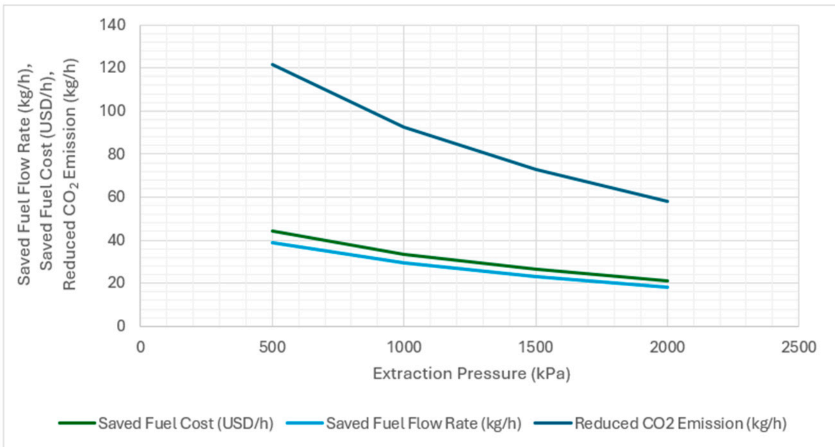

Figure 5. Saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions versus extraction pressure for turbine inlet pressure of 5000 kPa.

As seen in Figure 5, as the extraction pressure from the turbine increases, the saved fuel flow rate, saved fuel cost, and reduced CO_2 emission decrease. There is no relationship between the saved fuel flow rate, saved fuel cost, and reduced CO_2 emission values when a fraction of steam extraction from the turbine increases the process heat rate ratio. For an extraction pressure of 500 kPa, the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions are 38.591 kg/h, 44.166 USD/h, 121.563 kg/h, respectively. For an extraction pressure of 2000 kPa, the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions are 18.354 kg/h, 21.006 USD/h, 57.818 kg/h, respectively.

For a turbine inlet pressure of 5000 kPa, and a fraction of steam extracted from the turbine of 0.3, 0.4, or 0.5, the utilization factor and transformation energy equivalent factor of the cogeneration system versus the power and heat ratio are illustrated in Figure 6. As the utilization factor decreases, the energy equivalent factor increases in the power and heat ratio.

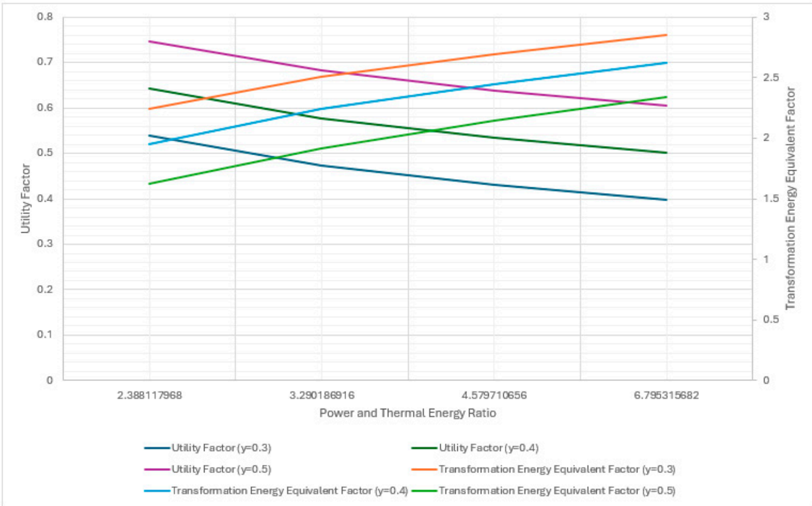

Figure 6. Utilization factor and transformation energy equivalent factor of cogeneration system versus power and heat ratio for turbine inlet pressure of 5000 kPa.

For a turbine inlet pressure of 6000 kPa, the following statements are true.

- For an extraction pressure of 500 kPa, y = 0.5, and the thermal efficiency, utilization factor, process heat rate, and electrical power are 0.358, 0.775, 764.4 kW, and 622.44 kW, respectively.
- For an extraction pressure of 2000 kPa, y = 0.5, and the thermal efficiency, utilization factor, process heat rate, and electrical power are 0.297, 0.628, 605.2 kW, and 517.94 kW, respectively.
- For an extraction pressure of 500 kPa, y = 0.3, and the thermal efficiency, utilization factor, process heat rate, and electrical power are 0.409, 0.562, 279.6 kW, and 712.025 kW, respectively.
- For an extraction pressure of 2000 kPa, y = 0.3, and the thermal efficiency, utilization factor, process heat rate, and electrical power are 0.372, 0.414, 77.53 kW, and 647.33 kW, respectively.
- For an extraction pressure of 500 kPa, the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions are 42.992 kg/h, 49.202 USD/h, and 135.426 kg/h, respectively.
- For an extraction pressure of 2000 kPa, the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions are 22.740 kg/h, 26.025 USD/h, and 71.633 kg/h, respectively.

For a turbine inlet pressure of 7000 kPa, the following statements are true.

- For an extraction pressure of 500 kPa, y = 0.5, and the thermal efficiency, utilization factor, process heat rate, and electrical power are 0.379, 0.804, 743.3 kW, and 631.37 kW, respectively.
- For an extraction pressure of 2000 kPa, y = 0.5, and the thermal efficiency, utilization factor, process heat rate, and electrical power are 0.318, 0.651, 581.4 kW, and 529.34 kW, respectively.
- For an extraction pressure of 500 kPa, y = 0.3, and the thermal efficiency, utilization factor, process heat rate, and electrical power are 0.432, 0.585, 267 kW, and 719.245 kW, respectively.
- For an extraction pressure of 2000 kPa, y = 0.3, and the thermal efficiency, utilization factor, process heat rate, and electrical power are 0.394, 0.431, 63.3 kW, and 656.165 kW, respectively.
- For an extraction pressure of 500 kPa, the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions are 46.968 kg/h, 53.752 USD/h, and 147.951 kg/h, respectively.

- For an extraction pressure of 2000 kPa, the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions are 26.716 kg/h, 30.575 USD/h, and 84.157 kg/h, respectively.

For a turbine inlet pressure of 8000 kPa, the effect of the extraction pressure and fraction of steam extracted from the turbine to be used for the process and that of the feedwater heater on the efficiency and utilization factor are illustrated in Figure 7.

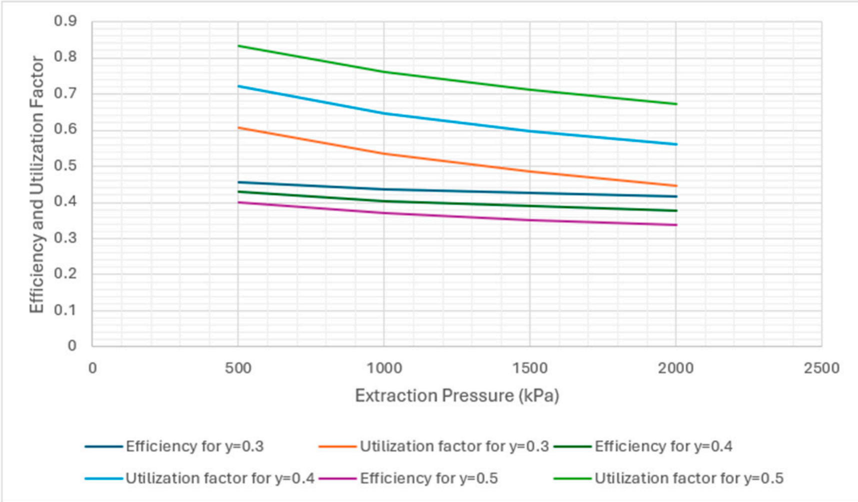

Figure 7. Efficiency and utilization factor versus extraction pressure for turbine inlet pressure of 8000 kPa.

As seen in Figure 7, as the extraction pressure from the turbine increases, the utilization factor and thermal efficiency decrease. As the fraction of steam extracted from the turbine increases, the utilization factor increases but the thermal efficiency decreases. For an extraction pressure of 500 kPa, y = 0.5, the thermal efficiency and utilization factor are 0.401 and 0.833, respectively. For an extraction pressure of 2000 kPa, y = 0.5, and the thermal efficiency and utilization factor are 0.338 and 0.672, respectively. For an extraction pressure of 500 kPa, y = 0.3, and the thermal efficiency and utilization factor are 0.455 and 0.608, respectively. For an extraction pressure of 2000 kPa, y = 0.3, and the thermal efficiency and utilization factor are 0.416 and 0.446, respectively. The thermal efficiency and utilization factors are inversely proportional ay the same extraction pressure of the turbine.

For a turbine inlet pressure of 8000 kPa, the effect of the extraction pressure and fraction of steam extracted from the turbine to be used for the process and that of the feedwater heater on the process heat rate and electrical power are illustrated in Figure 8.

As seen in Figure 8, as the extraction pressure from the turbine increases, the process heat rate and electrical power decrease. As the fraction of steam extracted from the turbine increases, the process heat rate increases but the electrical power decreases. For an extraction pressure of 500 kPa, y = 0.5, and the process heat rate and electrical power are 723.4 kW and 636.595 kW, respectively. For an extraction pressure of 2000 kPa, y = 0.5, and the process heat rate and electrical power are 559 kW and 537.13 kW, respectively. For an extraction pressure of 500 kPa, y = 0.3, and the process heat rate and electrical power are 255.1 kW and 722.855 kW, respectively. For an extraction pressure of 2000 kPa, y = 0.3, and the process heat rate and electrical power are 49.83 kW and 661.39 kW, respectively. The process heat rate and electrical power are inversely proportional at the same extraction pressure of the turbine.

For a turbine inlet pressure of 8000 kPa, the effect of the extraction pressure and fraction of steam extracted from the turbine to be used for the process and that of the feedwater heater on the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions are illustrated in Figure 9.

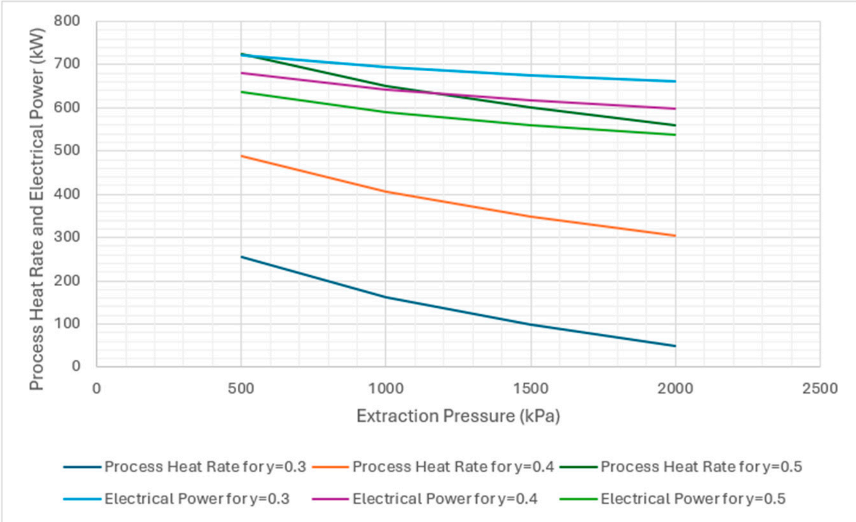

Figure 8. Process heat rate and electrical power versus extraction pressure for turbine inlet pressure of 8000 kPa.

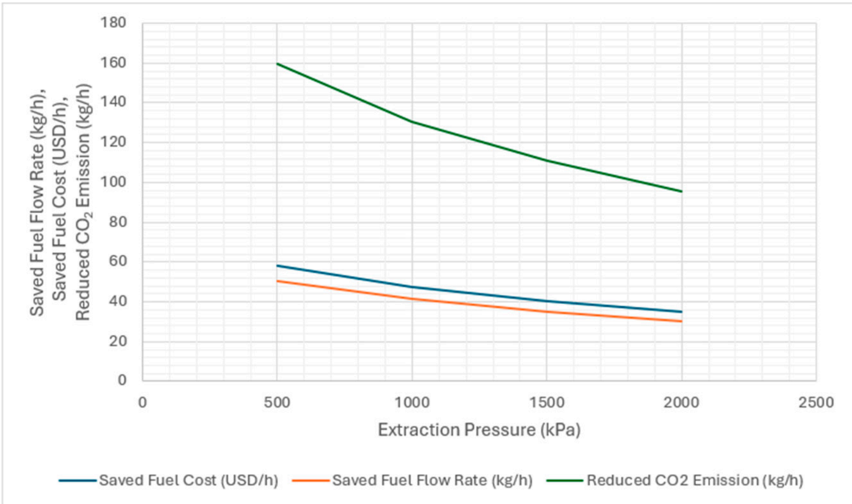

Figure 9. Saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions versus extraction pressure for turbine inlet pressure of 8000 kPa.

As seen in Figure 9, as the extraction pressure from the turbine increases, the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions decrease. There is no relationship between the saved fuel flow rate, saved fuel cost, and reduced CO_2 emission values, with the fraction of steam extraction from the turbine. For an extraction pressure of 500 kPa, the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions are 50.641 kg/h, 57.955 USD/h, and 159.519 kg/h, respectively. For an extraction pressure of 2000 kPa, the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions are 30.374 kg/h, 34.761 USD/h, and 95.678 kg/h, respectively.

For a turbine inlet pressure of 9000 kPa, the following statements are true.

- For an extraction pressure of 500 kPa, y = 0.5, and the thermal efficiency, utilization factor, process heat rate, and electrical power are 0.422, 0.863, 704.1 kW, and 638.875 kW, respectively.
- For an extraction pressure of 2000 kPa, y = 0.5, and the thermal efficiency, utilization factor, process heat rate, and electrical power are 0.357, 0.694, 537.3 kW, and 541.785 kW, respectively.
- For an extraction pressure of 500 kPa, y = 0.3, and the thermal efficiency, utilization factor, process heat rate, and electrical power are 0.478, 0.630, 243.5 kW, and 723.615 kW, respectively.
- For an extraction pressure of 2000 kPa, y = 0.3, and the thermal efficiency, utilization factor, process heat rate, and electrical power are 0.438, 0.461, 36.8 kW, and 663.67 kW, respectively.

- For an extraction pressure of 500 kPa, the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions are 54.070 kg/h, 61.881 USD/h, and 170.323 kg/h, respectively.
- For an extraction pressure of 2000 kPa, the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions are 33.803 kg/h, 38.686 USD/h, and 106.481 kg/h, respectively.

For a turbine inlet pressure of 10,000 kPa, the effect of the extraction pressure and fraction of steam extracted from the turbine to be used for the process and that of the feedwater heater on the efficiency and utilization factor are illustrated in Figure 10.

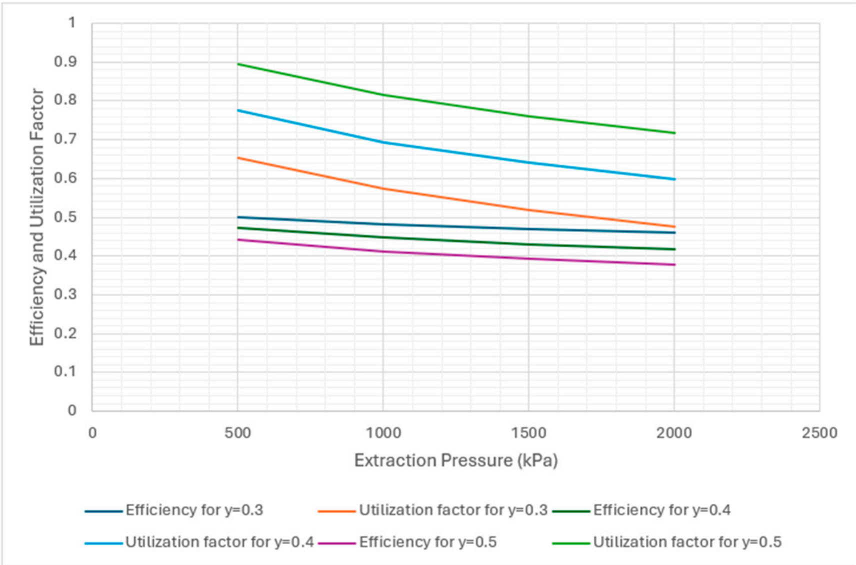

Figure 10. Efficiency and utilization factor versus extraction pressure for turbine inlet pressure of 10,000 kPa.

As seen in Figure 10, as the extraction pressure from the turbine increases, the utilization factor and thermal efficiency decrease. As the fraction of steam extracted from the turbine increases, the utilization factor increases but the thermal efficiency decreases. For an extraction pressure of 500 kPa, y = 0.5, and the thermal efficiency and utilization factor are 0.443 and 0.895, respectively. For an extraction pressure of 2000 kPa, y = 0.5, and the thermal efficiency and utilization factor are 0.377 and 0.717, respectively. For an extraction pressure of 500 kPa, y = 0.3, and the thermal efficiency and utilization factor are 0.501 and 0.654, respectively. For an extraction pressure of 2000 kPa, y = 0.3, and the thermal efficiency and utilization factor are 0.460 and 0.476, respectively. The thermal efficiency and utilization factors are inversely proportional at the same extraction pressure of the turbine.

For the turbine inlet pressure of 10,000 kPa, the effect of the extraction pressure and fraction of steam extracted from the turbine to be used for the process and that of the feedwater heater on the process heat rate and electrical power are illustrated in Figure 11.

As seen in Figure 11, as the extraction pressure from the turbine increases, the process heat rate and electrical power decrease. As the fraction of steam extracted from the turbine increases, the process heat rate increases but the electrical power decreases. For an extraction pressure of 500 kPa, y = 0.5, the process heat rate and electrical power are 685 kW and 638.495 kW, respectively. For an extraction pressure of 2000 kPa, y = 0.5, the process heat rate and electrical power are 515.8 kW and 543.78 kW, respectively. For an extraction pressure of 500 kPa, y = 0.3, the process heat rate and electrical power are 232 kW and 721.715 kW, respectively. For an extraction pressure of 2000 kPa, y = 0.3, the process heat rate and electrical power are 23.91 kW and 663.195 kW, respectively. The process heat rate and electrical power are inversely proportional at the same extraction pressure of the turbine.

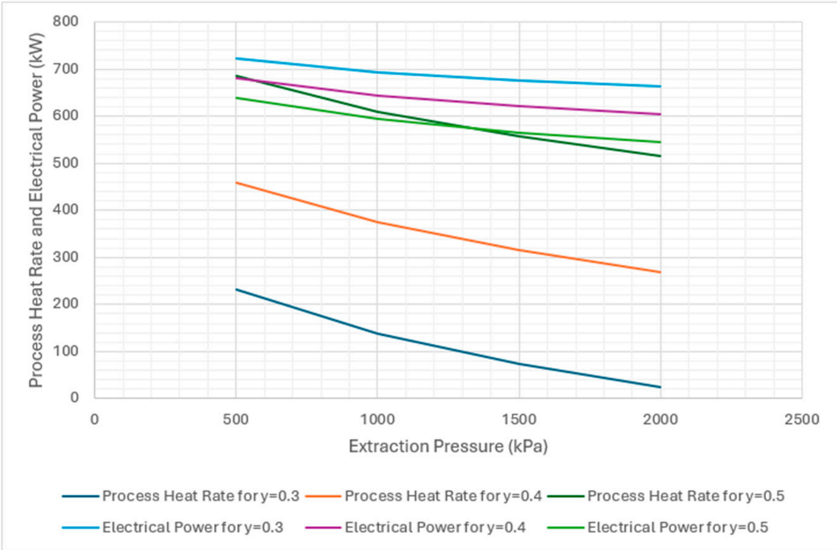

Figure 11. Process heat rate and electrical power versus extraction pressure for turbine inlet pressure of 10,000 kPa.

For a turbine inlet pressure of 10,000 kPa, the effect of the extraction pressure and fraction of steam extracted from the turbine to be used for the process and that of the feedwater heater on the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions are illustrated in Figure 12.

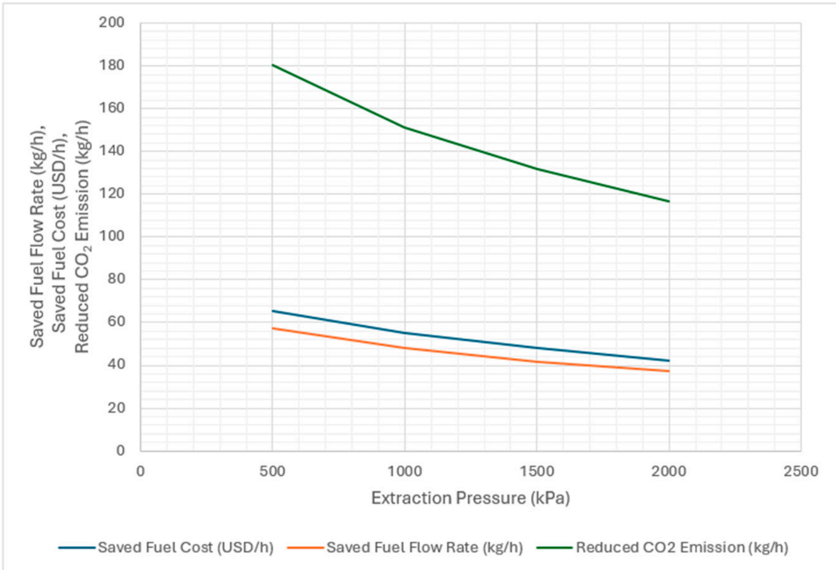

Figure 12. Saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions versus extraction pressure for turbine inlet pressure of 10,000 kPa.

As seen in Figure 12, as the extraction pressure from the turbine increases, the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions decrease. There is no relationship between the saved fuel flow rate, saved fuel cost, and reduced CO_2 emission values, with the fraction of steam extraction from the turbine increasing the process heat rate ratio. For an extraction pressure of 500 kPa, the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions are 57.325 kg/h, 65.606 USD/h, and 180.576 kg/h, respectively. For an extraction pressure of 2000 kPa, the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions are 37.051 kg/h, 42.403 USD/h, and 116.711 kg/h, respectively.

For a turbine inlet pressure of 10,000 kPa and a fraction of steam extracted from the turbine of 0.3, 0.4, and 0.5, the utilization factor and transformation energy equivalent factor of the cogeneration system versus power and heat ratio are illustrated in Figure 13. As the utilization factor decreases, the energy equivalent factor increases in the power and heat ratio.

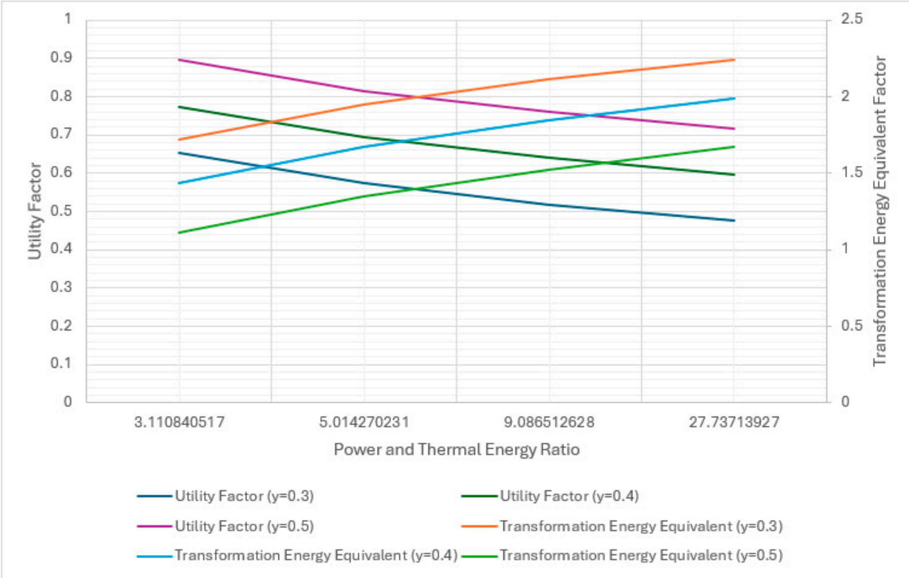

Figure 13. Utilization factor and transformation energy equivalent factor of cogeneration system versus power and heat ratio for turbine inlet pressure of 10,000 kPa.

The marine diesel engine waste heat-assisted cogeneration power plant modified with regeneration onboard a ship provides a high thermal efficiency and utilization factor. Generally, as the extraction pressure from the turbine increases, the utilization factor and thermal efficiency decrease. As the extraction pressure from the turbine increases, the saved fuel flow rate, saved fuel cost, and reduced CO_2 emissions decrease. The transformation energy equivalent factor increases with an increasing power and heat ratio. For an optimal value, the utilization and transformation energy equivalent factors of a cogeneration system versus the power and heat ratio for a cogeneration system with various turbine inlet pressures and fractions of steam extracted from the turbine are calculated.

In regions with small power–heat ratio values, the thermal energy is practically dominant, while in regions with high power–heat ratio values, the electrical energy is practically dominant.

Verification

In this study, the efficiency and utilization factors of the proposed system are calculated to be between 28.89% and 48.18% and 39.71% and 86.36%, respectively. The specific data for the system configuration are unavailable. For comparison, the internal combustion engine cogeneration system specifications of some manufacturers are provided in Table 4. Generally, this study has higher efficiency and utilization factors (overall efficiency) than those reported in the existing literature.

Table 4. Internal combustion engine cogeneration system specifications [29].

Parameters	Manufacturer			
	Honda (Minato, Japan)	**Coast-Intelligen (Vista, CA, USA)**	**Tecogen (North Billerica, MA, USA)**	**MAN (Munich, Germany)**
Electrical capacity (kW)	1	55	60	100
Efficiency (%)	21.3	30	26.4	30.6
Overall efficiency (%) HHV	85	78	83.1	81

5. Conclusions

In this study, the thermodynamic analysis of a marine engine waste heat-assisted cogeneration power plant modified with regeneration onboard a ship is performed. By using the main engine jacket water and exhaust heat for electricity and heat generation on the ship, the amount of fuel consumed by the boiler is reduced and CO_2 emissions are reduced. The thermal efficiency, utilization, and transformation energy equivalent factors are calculated according to the fraction of steam extracted from the turbine and extract pressure.

For a given turbine inlet pressure and fraction of steam extracted from the turbine, the optimum operating value for the power–heat ratio can be obtained from the intersection of the utilization factor and the transformation energy equivalent factor.

This study shows that the proposed system can achieve an efficiency of 48.18% and utilization factor of 86.36%, savings of up to 57.325 kg/h in fuel, 65.606 USD/h in fuel costs, and 180.576 kg/h in CO_2 emissions per unit mass flow rate through a steam turbine onboard a ship.

Author Contributions: Investigation, H.K.; formal analysis, C.E.; methodology, H.K. and C.E.; project administration, H.K.; resources, C.E.; validation, C.E.; writing—original draft, H.K.; writing—review and editing, C.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data generated or analyzed during this study are included in this published article.

Conflicts of Interest: No conflicts of interest exist in the submission of this manuscript, and the manuscript is approved by all authors for publication. The authors declare no conflicts of interest.

Appendix A

```
"Input Data"
y=0.3–0.4-0.5 "fraction of steam extracted from the turbine for feedwater and process heater."
P[6] = 5000-6000-7000-8000-9000-10000 [kPa]
T[6] = 350 [°C]
P_extract=500-1000-1500-2000 [kPa]
P[7] = P_extract
P_cond=10 [kPa]
P[8] = P_cond
m_dot=1 [kg/s]
Eta_turb= 85/100
Eta_pump =85/100
P[1] = P[8]
P[2] = P[7]
P[3] = P[7]
P[4] = P[7]
P[5] = P[6]
P[9] = P[7]
"Pump 1 analysis"
Fluid$='Steam_IAPWS'
h[1]=enthalpy(Fluid$,P=P[1],x=0)
v1=volume(Fluid$,P=P[1],x=0)
s[1]=entropy(Fluid$,P=P[1],x=0)
T[1]=temperature(Fluid$,P=P[1],x=0)
```

```
w_pump1_s=v1*(P[2]-P[1])
w_pump1=w_pump1_s/Eta_pump
h[1]+w_pump1=h[2]
s[2]=entropy(Fluid$,P=P[2],h=h[2])
T[2]=temperature(Fluid$,P=P[2],h=h[2])
“Open Feedwater Heater Analysis:”
z*h[7]+(1-y)*h[2]=(1-y+z)*h[3] “fraction of steam extracted for the closed feedwater heater”.
h[3]=enthalpy(Fluid$,P=P[3],x=0)
T[3]= temperature(Fluid$,P=P[3],x=0)
s[3]=entropy(Fluid$,P=P[3],x=0)
"Process heater analysis:"
(y-z)*h[7]=q_process+(y-z)*h[9]
Q_dot_process=m_dot*(y-z)-q_process
h[9]=enthalpy(Fluid$,P=P[9],x=0)
T[9]=temperature(Fluid$,P=P[9],x=0)
s[9]=entropy(Fluid$,P=P[9],x=0)
“Mixing chamber at 3,4 and 9.”
(y-z)*h[9]+(1-y+z)*h[3]=1*h[4]
T[4]=temperature(Fluid$,P=P[4],h=h[4])
s[4]=entropy(Fluid$,P=P[4],h=h[4])
“Boiler condensate pump or Pump 2 analysis”
v4=volume(Fluid$,P=P[4],x=0)
w_pump2_s=v4*(P[5]-P[4])
w_pump2=w_pump2_s/Eta_pump
h[4]+w_pump2=h[5]
s[5]=entropy(Fluid$,P=P[5],h=h[5])
T[5]=temperature(Fluid$,P=P[5],h=h[5])
h[10]=enthalpy(Fluid$,P=P[5],x=0)
T[10]=temperature(Fluid$,P=P[5],h=h[10])
“Boiler analysis”
q_in+h[10]=h[6]
h[6]= enthalpy(Fluid$,T=T[6],P=P[6])
s[6]= entropy(Fluid$,T=T[6],P=P[6])
“Turbine analysis”
ss[7]=s[6]
hs[7]=enthalpy(Fluid$,s=ss[7],P=P[7])
Ts[7]=temperature(Fluid$,s=ss[7],P=P[7])
h[7]=h[6]-Eta_turb*(h[6]-hs[7])
T[7]=temperature(Fluid$,P=P[7],h=h[7])
s[7]=entropy(Fluid$,P=P[7],h=h[7])
ss[8]=s[7]
hs[8]=enthalpy(Fluid$,s=ss[8],P=P[8])
Ts[8]=temperature(Fluid$,s=ss[8],P=P[8])
h[8]=h[7]-Eta_turb*(h[7]-hs[8])
T[8]=temperature(Fluid$,P=P[8],h=h[8])
s[8]=entropy(Fluid$,P=P[8],h=h[8])
h[6]=y*h[7]+(1-y)*h[8]+w_turb
“Condenser analysis”
(1-y)*h[8]=q_out+(1-y)*h[1]
“Cycle Statistics”
w_net=w_turb-((1-y)*w_pump1+w_pump2)
Eta_th=w_net/q_in
W_dot_net=m_dot*w_net
```

References

1. Yan, R.; Yang, D.; Wang, T.; Mo, H.; Wang, S. Improving ship energy efficiency: Models, methods, and applications. *Appl. Energy* **2024**, *368*, 123132. [CrossRef]
2. Godet, A.; Nurup, J.; Saber, J.; Panagakos, G.; Barfod, M. Operational cycles for maritime transportation: A benchmarking tool for ship energy efficiency. *Transp. Res. Part D Transp. Environ.* **2023**, *121*, 103840. [CrossRef]
3. Dotto, A.; Satta, F. Techno-economic optimization of hybrid-electric power plants onboard cruise ships. *Energy Convers. Manag.* **2023**, *20*, 100436. [CrossRef]
4. Kistner, L.; Bensmann, A.; Minke, C.; Rauschenbach, R. Comprehensive techno-economic assessment of power technologies and synthetic fuels under discussion for ship applications. *Renew. Sustain. Energy Rev.* **2023**, *183*, 113459. [CrossRef]
5. Saksa, P.; Lehtoranta, K.; Kuittinen, N.; Järvinen, A.; Jalkanen, J.; Johnson, K.; Jung, H.; Ntziachristos, L.; Gagné, S.; Takahashi, C.; et al. Reduction in greenhouse gas and other emissions from ship engines: Current trends and future options. *Prog. Energy Combust. Sci.* **2023**, *94*, 101055. [CrossRef]
6. Dotto, A.; Satta, F.; Campora, U. Energy, environmental, and economic investigations of cruise ships powered by alternative fuels. *Energy Convers. Manag.* **2023**, *285*, 117011. [CrossRef]
7. Lebedevas, S.; Čepaitis, T. Methodological Solutions for Predicting Energy Efficiency of Organic Rankine Cycle Waste Heat Recovery Systems Considering Technological Constraints. *J. Mar. Sci. Eng.* **2024**, *12*, 1303. [CrossRef]
8. Elkafas, A. Thermodynamic Analysis and Economic Assessment of Organic Rankine Cycle Integrated with Thermoelectric Generator Onboard Container Ship. *Processes* **2024**, *12*, 355. [CrossRef]
9. Rigogiannis, N.; Roussos, I.; Pechlivanis, C.; Bogatsis, I.; Kyritsis, A.; Papanikolaou, N.; Loupis, M. Study of an LLC Converter for Thermoelectric Waste Heat Recovery Integration in Shipboard Microgrids. *Technologies* **2024**, *12*, 67. [CrossRef]
10. Iliev, I.; Filimonova, A.; Chichirov, A.; Chichirova, N.; Pechenkin, A.; Vinogradov, A. Theoretical and Experimental Studies of Combined Heat and Power Systems with SOFCs. *Energies* **2023**, *16*, 1898. [CrossRef]
11. Atănăsoae, P.; Pentiuc, R.; Milici, L. Opportunity Analysis of Cogeneration and Trigeneration Solutions: An Application in the Case of a Drug Factory. *Energies* **2022**, *15*, 2737. [CrossRef]
12. Pacheco-Reyes, A.; Jiménez-García, J.; Hernández-Magallanes, J.; Shankar, R.; Rivera, W. Energy, Exergy, and Economic Analysis of a New System for Simultaneous Power Production and Cooling Operating with an Ammonia–Water Mixture. *Processes* **2024**, *12*, 1288. [CrossRef]
13. Esfahani, I.; Ifaei, P. Optimal Design of a Renewable-Energy-Driven Integrated Cooling–Freshwater Cogeneration System. *Processes* **2024**, *12*, 1164. [CrossRef]
14. Agberegha, L.; Aigba, P.; Nwigbo, S.; Onoroh, F.; Samuel, O.; Bako, T.; Der, O.; Ercetin, A.; Sener, R. Investigation of a Hybridized Cascade Trigeneration Cycle Combined with a District Heating and Air Conditioning System Using Vapour Absorption Refrigeration Cooling: Energy and Exergy Assessments. *Energies* **2024**, *17*, 1295. [CrossRef]
15. Tinoco, D.; Santos, M.; Mero-Benavides, M.; Patiño, O.; Lozano, A.; Blanco, A. Simulation and Exergoeconomic Analysis of a Trigeneration System Based on Biofuels from Spent Coffee Grounds. *Energies* **2023**, *16*, 1816. [CrossRef]
16. Gospić, I.; Glavan, I.; Poljak, I.; Mrzljak, V. Energy, Economic and Environmental Effects of the Marine Diesel Engine Trigeneration Energy Systems. *J. Mar. Sci. Eng.* **2021**, *9*, 773. [CrossRef]
17. Tien, W.; Yeh, R.; Hong, J. Theoretical analysis of cogeneration system for ships. *Energy Convers. Manag.* **2007**, *48*, 1965–1974. [CrossRef]
18. Liang, Y.; Shu, G.; Tian, H.; Liang, X.; Wei, H.; Liu, L. Analysis of electricity–cooling cogeneration system based on RC–ARS combined cycle aboard ship. *Energy Convers. Manag.* **2013**, *76*, 1053–1060. [CrossRef]
19. Wang, Z.; Lebedevas, S.; Rapalis, P.; Zaglinskis, J.; Mickeviciene, R.; Djackov, V.; Liu, X. Use of LNG Cold Potential in the Cogeneration Cycle of Ship Power Plants. *J. Mar. Sci. Eng.* **2020**, *8*, 720–743. [CrossRef]
20. Brozičević, M.; Martinović, D.; Kralj, P. Techno-economic analysis of the cogeneration process on board ships. *J. Sustain. Dev. Transp. Logist.* **2017**, *2*, 6–15. [CrossRef]
21. Liang, Y.; Shu, G.; Tian, H.; Wei, H.; Liang, X.; Liu, L.; Wang, X. Theoretical analysis of a novel electricity–cooling cogeneration system (ECCS) based on cascade use of waste heat of the marine engine. *Energy Convers. Manag.* **2014**, *85*, 888–894. [CrossRef]
22. Liua, X.; Nguyena, M.; Hea, M. Performance analysis and optimization of an electricity-cooling cogeneration system for waste heat recovery of marine engine. *Energy Convers. Manag.* **2020**, *214*, 112887. [CrossRef]
23. Qu, J.; Feng, Y.; Zhu, Y.; Zhou, S.; Zhang, W. Design and thermodynamic analysis of a combined system including steam Rankine cycle, organic Rankine cycle, and power turbine for marine low-speed diesel engine waste heat recovery. *Energy Convers. Manag.* **2021**, *245*, 114580. [CrossRef]
24. Ouyang, T.; Wang, Z.; Zhao, Z.; Lu, J.; Zhang, M. An advanced marine engine waste heat utilization scheme: Electricity-cooling cogeneration system integrated with heat storage device. *Energy Convers. Manag.* **2021**, *235*, 113955. [CrossRef]
25. Qun, S.; Xuan, W.; Hua, T.; Cai, L.; Yu, L.; Peng, L. Analysis of an electricity-cooling cogeneration system for waste heat recovery of gaseous fuel engines. *Sci. China Technol. Sci.* **2015**, *58*, 37–46.
26. International Maritime Organization. Improving the Energy Efficiency of Ships. Available online: https://www.imo.org (accessed on 21 August 2024).
27. Çengel, Y.A.; Boles, M.A. *Thermodynamics: An Engineering Approach*; McGraw-Hill Education: New York, NY, USA, 2015.

28. Rules for the Classification of Naval Ships. Available online: https://www.turkloydu.org/pdf-files/turk-loydu-kurallari/cilt-e/chapter-101-naval-ship-technology-classification-and-surveys-2015.pdf (accessed on 21 August 2024).
29. Onovwiona, H.; Ugursal, V. Residential cogeneration systems: Review of the current technology. *Renew. Sustain. Energy Rev.* **2006**, *10*, 389–431. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.