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Performance Analysis of Combined Gas-Electric Steam Turbine System as Main Propulsion for Small-scale LNG Carrier Ships

Muhammad Arif Budiyanto[1*], Sultan Alif Zidane[1], Gerry Liston Putra[1], Achmad Riadi[1], Riezqa Andika[2], Gerasimos Theotokatos[3]

[1]*Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus Baru UI, Depok 16424, Indonesia*
[2]*Department of Chemical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus Baru UI, Depok 16424, Indonesia*
[3]*Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, G4 0LZ, UK*

Abstract. The development of liquefied natural gas (LNG) carrier ships is increasing rapidly along with the demand for alternative energy sources. This study aims to analyze the performance of an LNG-fueled propulsion system for a small-scale LNG carrier ship with a combination gas-electric steam turbine system (COGES). The performance of the propulsion system is analyzed based on the power output generation and the environmental effect of the system. The total power output was evaluated using thermodynamic analysis and the environmental impact was measured by carbon emissions using the life-cycle assessment approach. The analysis results show the COGES propulsion system potentially generates total power of 7600 kW at peak load. The desired ship operational speed of 12 knots can be achieved at 24% load of the total power output. The COGES propulsion system also indicates a low emission than other systems with a carbon emission is 0.149 $kgCO_2/kWh$.

Keywords: COGES; Propulsion system; Small-scale LNG carrier

1. Introduction

In the transportation industry, natural gas is a promising alternative fuel source that offers benefits such as improved combustion efficiency and a decrease in greenhouse gas emissions (Cheenkachorn, Poompipatpong, and Ho, 2013). Among the natural gas alternative fuel candidates, liquefied natural gas (LNG) is a promising one due to its higher safety, easier transportation, and storage capacity (Djermouni and Ouadha, 2017). The ability to transport LNG over long distances and in large quantities from natural gas producers and consumers is another advantage, therefore an option that may be done is to liquefy natural gas (Aspelund and Gundersen, 2009). LNG is converted from natural gas to a liquid phase through a liquefaction plant, which reduces its volume and enables LNG carrier ships to transport it in liquid cargo (Głomski and Michalski, 2011).

LNG carriers are ships equipped with tanks designed to transport liquefied natural gas with temperatures below −162 °C (Bai and Jin, 2015). LNG carriers vary in cargo capacity, ranging from small capacities starting at 1000 m^3 to the largest cargo capacity currently

*Corresponding author's email: ma.budiyanto@ui.ac.id, Tel.: +62-217270032; Fax.: +62-217270033
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reaching 266,000 m^3. A Small-scale LNG carrier is an LNG carrier that has a carrying capacity of up to 40,000 m^3 (Guerrero, 2019). The small-scale LNG carrier is used for remote areas with shallow water draught. In its development, the use of small-scale LNG carriers needs to be reviewed in terms of economic value and transportation costs (Budiyanto *et al.*, 2020).

In transporting LNG using sea transportation, it is necessary to pay attention to the use of the propulsion system to obtain efficiency and economic feasibility considerations. International Maritime Organization (IMO) has formulated an energy efficiency design index policy for the ships. According to research based on data from registered ship engines, tankers and gas carriers are among the ship types that produce the most carbon emissions (Budiyanto, Adha, and Prayoga, 2022). The small-scale LNG carrier thus is designed to feature a propulsion system that uses natural gas or LNG as fuel to facilitate more affordable and environmentally friendly gas transportation (Wibisana and Budiyanto, 2021).

In terms of energy efficiency, numerous alternative propulsion systems with higher efficiency values have been proposed including the dual fuel diesel engine and the combined cycle. The ship propulsion system mainly consists of three main parts, i.e.: the prime mover, the transmission system, and the ship propulsion device. The design of the ship's propulsion system will depend on the type of ship, the main size, the ship's speed, the stern model, and the hull model (Lin *et al.*, 2020). The propulsion system of the main part of the ship is closely related to the thermal power generation cycle (Pamik *et al.*, 2022). Thermal power generation is a cycle of burning fuel to produce energy to produce electricity that will be used to drive the ship's propulsion system (Gaber *et al.*, 2020).

Combined gas turbine electricity and steam (COGES) is a propulsion system that uses a gas turbine to generate electric power, which is then utilized to drive an electric motor that is connected to a shaft propeller (Dotto, Campora, and Satta, 2021). To increase the performance of the gas turbine, several LNG vessels with COGES systems utilize exhaust gas to reheat the steam and used it as a heat recovery steam generator (Ziółkowski *et al.*, 2019). Several studies related to the COGES system have been conducted to improve the total efficiency of the system. Meanwhile, studies on the environmental impacts of the application of small-scale LNG carriers are still limited.

The purpose of this study is to analyze the proposed COGES propulsion system for a small-scale LNG carrier. The contribution of this study is twofold, which is providing a comparison of the power output of COGES with conventional systems and understanding the environmental impact of the proposed system.

2. Research Methods

2.1. Case Study of LNG Carriers

The case study used in this research is a small-scale LNG carrier with a capacity of 7500 m^3. The size of small LNG carriers has capacities varying from 1000 - 40,000 m^3 (TGE-Marine, 2022; Wärtsilä, 2022; Bai and Jin, 2015). No classification regulates the dimensions of small LNG carriers. The use of small LNG carriers is attractive for short-distance shipping inter islands with limited draft depths and small amounts of cargo (Wibisana and Budiyanto, 2021). Table 1 shows the main dimensions of the small-scale LNG carrier used as a case study. The ship data is used as an initial reference for calculating ship resistance which can be used as an initial assumption of ship power requirements as shown in Figure 1. In this study, the hull design of a small LNG carrier was designed using the spiral method. The amount of power needed is calculated based on hull design data using ship resistance calculations. The assumption is based on the resistance calculation using the Holtrop method. The calculation of ship resistance uses the Holtrop method which is suitable for cargo ship types including tankers (Birk, 2019). From the results of the calculation of the ship's resistance, it can be calculated that the power required for the ship to move at a service speed of 12 knots is 1832 kW, and at a maximum speed of 14 knots is 3377 kW.

Table 1 Ship dimensions of the case study

Ship Dimension	
Length Overall	: 117.8 m
Length between perpendicular	: 110.2 m
Beam	: 18.6 m
Depth	: 10.6 m
Draft	: 7.15 m
Service Speed	: 12 Knots
Cargo Tank Capacity	: 7500 m^3
Boil-off Gas rate	: 0.3%/day

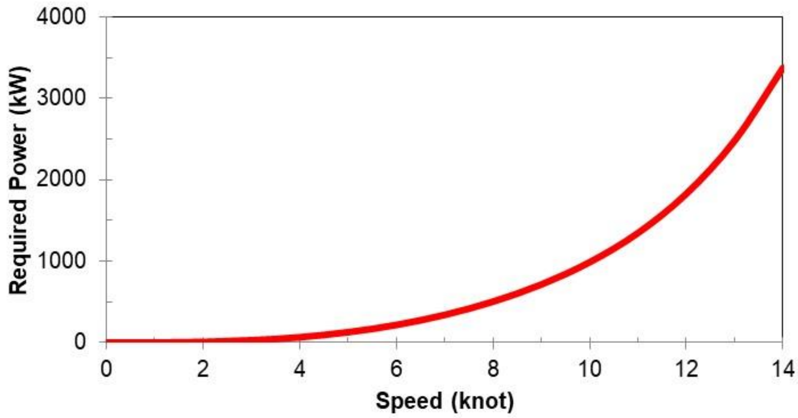

Figure 1 The required power at the desired speed of the case study

2.2. Proposed Design of COGES Propulsion System

The design of the small-scale LNG carrier propulsion system proposed in this study is COGES which consists of two power generators each sourced from a gas turbine and a heat recovery steam generator. The system diagram of the proposed COGES design is shown in Figure 2. The design of the COGES propulsion system consists of several main components, namely gas turbines, heat recovery steam generators, condensers, deaerators, pumps, and generators. The thermodynamic system analysis of the proposed COGES design was carried out using the Cycle-Tempo application to obtain the output power generation and total efficiency of the design system. Cycle-Tempo is commercial software to analyze and optimize the thermodynamics of the energy system (Asimptote, 2023), which includes a combined cycle and organic Rankine cycle (Muslim *et al.*, 2019). The equation used in this application is based on the thermodynamic process of the law of energy balance. Equation 1 of the law of conservation of mass, Equation 2 of the law of energy balance, and Equation 3 of the law of exergy balance are used in the calculation (Budiyanto, Nasruddin, and Nawara, 2020). In the law of exergy balance, an exergy rate was required, therefore the equation was modified into Equation 4 (Ahmadi *et al.*, 2017). In these equations h is enthalpy in (kJ/kg), $h_{ambient}$ is environment enthalpy/ambient (kJ/kg), s is entropy environment (kJ/(kg.K)), $s_{ambient}$ is environment entropy/ambient kJ/(kg.K), m is mass flow (kg/s), $T_{ambient}$ is environment temperature/ambient (K), Q_{in} is the calorie input of system (kW), W is performance output of the system (kW), and $E_{(x,n)}$ is exergy rate (kW).

$$\Sigma_{in}\dot{m} = \Sigma_{out}\,\dot{m} \tag{1}$$

$$\dot{Q} - \dot{W} = \Sigma_{out}\dot{m}.h - \Sigma_{in}\,\dot{m}.h \tag{2}$$

$$\dot{X}_{des} = \Sigma_{out}\left(1 - \frac{T_{ambient}}{T_n}\right).\dot{Q}_{in} - \dot{W} + \Sigma_{in}\dot{m}.E_x - \Sigma_{out}\dot{m}.E_x \tag{3}$$

$$\dot{E}_{x,n} = \dot{m}(h_n - h_{ambient} - T_{ambient}(s_n - s_{ambient})) \quad (4)$$

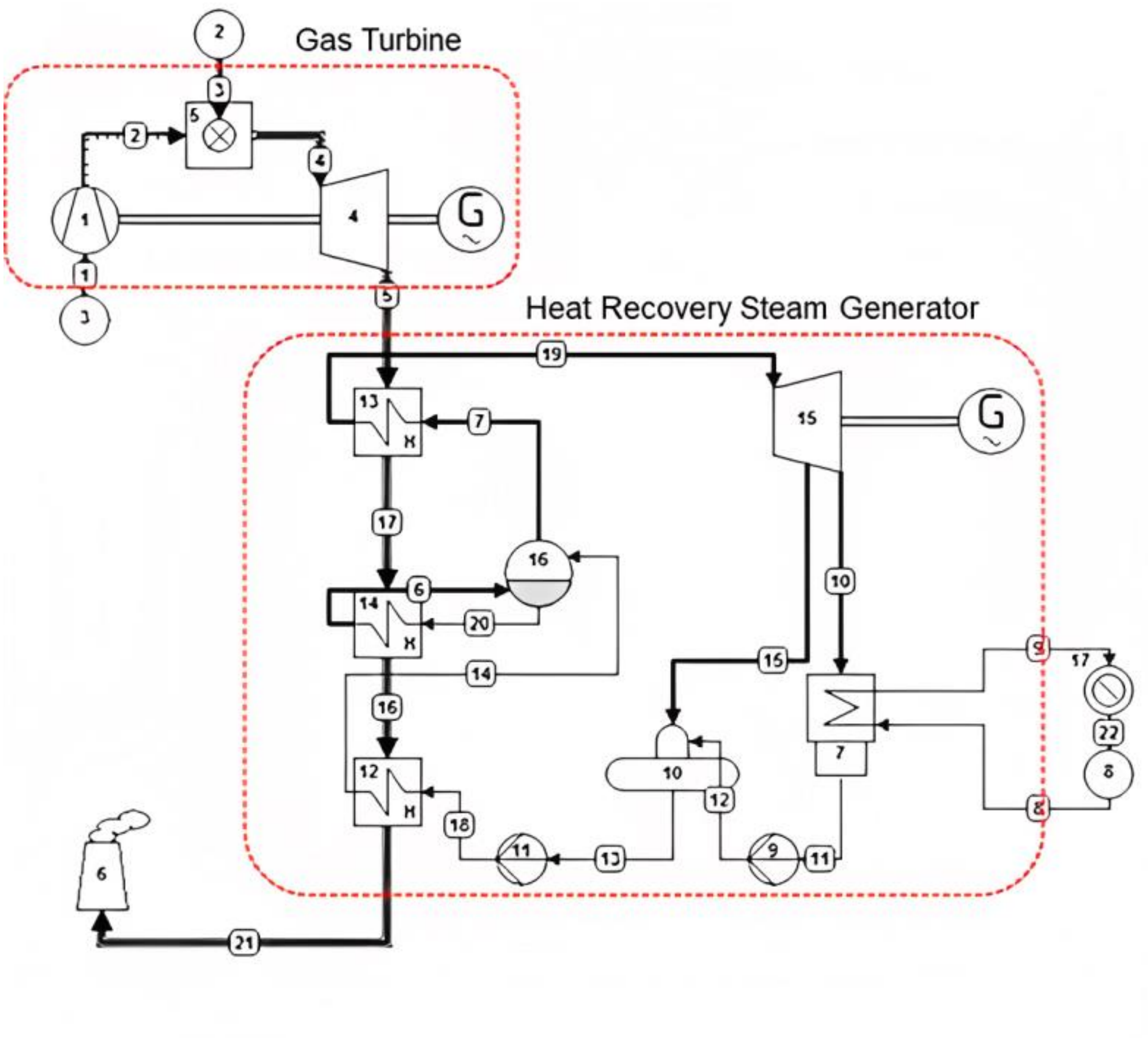

Figure 2 Proposed design of COGES propulsion system

An analysis of the effect of boiled gas (BOG) produced from the LNG carrier cargo tank was carried out to investigate the effect of BOG as turbine fuel on the performance of the system. The power output generated by the design system will also be influenced by the amount of fuel obtained from the BOG of the ship's cargo. It is necessary to take into account the amount of BOG produced by the ship. The ship's BOG is also influenced by the boil-off rate (BOR) of the number of shiploads, therefore several variations will be made based on the BOR of cargo starting from the range 0.1%-0.3% per day. Equation 5 shows the calculation of BOG, where V is LNG cargo volume (m^3), ρ is LNG density (kg/m^3), and t is shipping time (hours).

$$BOG = \frac{V \times \rho \times BOR \times t}{24} \quad (5)$$

2.3. Estimation of Carbon Emission

In this study, carbon emissions are estimated based on the power output (kWh) for each propulsion system. The estimation was carried out using the life cycle assessment software application, namely SimaPro (Goedkoop *et al.*, 2016). The damage assessment was achieved through the life cycle assessment in several categories, including ecosystem quality, resorts, human events, and climate change. The damage assessment analysis compares the output emissions produced by the COGES propulsion system to those produced by other propulsion systems such as the diesel propulsion system or the dual fuel diesel electric (DFDE) system. In such cases, the estimation of carbon emissions begins with the ship's activities as it approaches the port, which includes ship maneuvering and berthing (Dawangi and Budiyanto, 2021).

3. Results and Discussion

Performance analysis of the COGES was conducted by thermodynamic analysis to determine the amount of power output that can be generated by the designed system. The power output of the COGES propulsion system is shown in Figure 3. According to the thermodynamic analysis results, the proposed COGES potentially generate up to 7600 kW of power at full load. To attain the ship's operating speed of 12 knots, which requires 1832 kW, the COGES system only needs to load around 24% of the entire design load. These results are consistent with the power output trendline of other similar studies, which in this study also stated that the load needed to meet the ship's propulsion power requirements was 33% (Nirbito, Budiyanto, and Muliadi, 2020). This shows that the use of the COGES design system makes the work of the main components lighter so that the use of the system will be more durable because it does not always work at maximum load conditions. In actual operation, the power output produced by COGES is used to power all systems on board the ship in addition to the propulsion system.

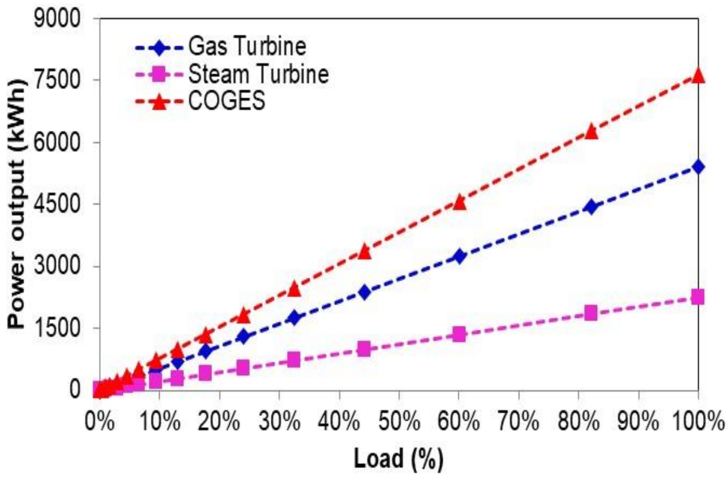

Figure 3 The power output of the COGES propulsion system

The condition of the system's performance is strongly influenced by the availability of fuels. The proposed COGES propulsion system is assumed to use boil-off gas. On LNG ships, the amount of boil-off gas naturally depends on the rate of evaporation that occurs in the cargo tanks and is a function of the length of the ship's journey. The relationship between the boil-off gas and sailing time is shown in Figure 4. With the use of the proposed COGES propulsion system, ships can take advantage of boil-off gas evaporation from the cargo tanks. The availability of boil-off gas is strongly influenced by the boil-off rate and the sailing time which is related to the ship's speed. To meet the fuel needs of ships with a ship speed of 12 knots, assuming a boil-off rate of 0.3% per day (Pamitran, Budiyanto, and Maynardi, 2019), it takes about 3 days of sailing. The longer the sailing time, the greater the result of boil-off gas so that it can be more profitable from an operational point of view.

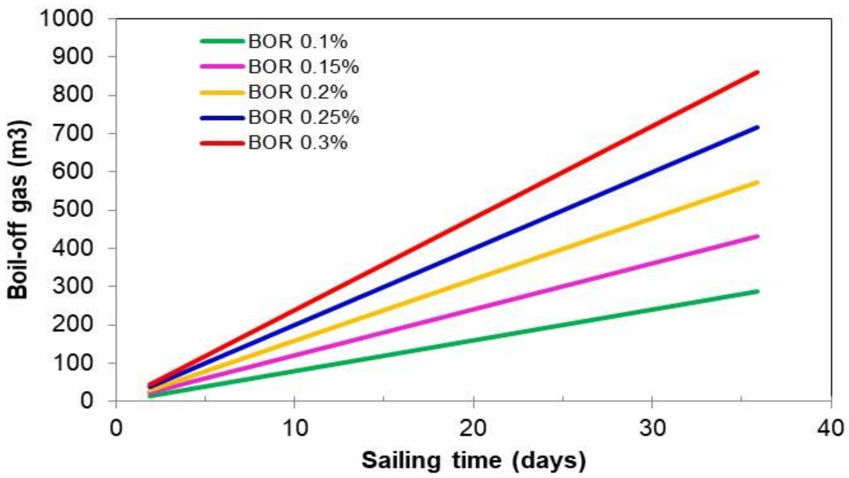

Figure 4 Variation of boil-off of gas results during sailing time

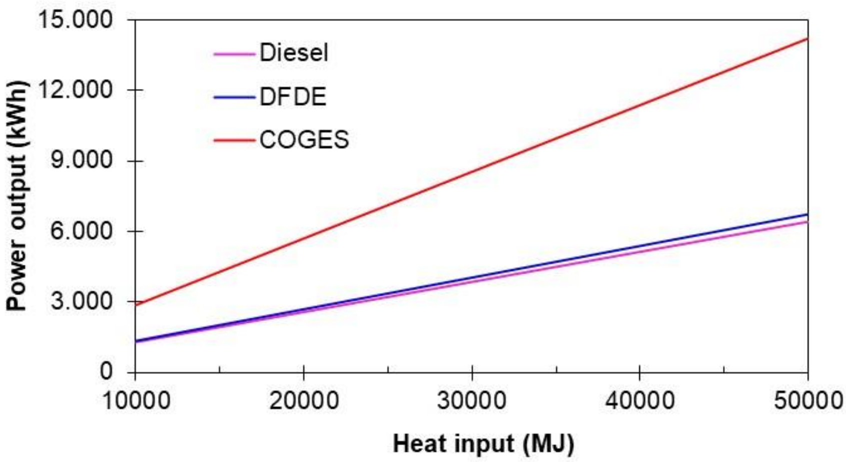

Figure 5 Comparison of the power output from the 3 different propulsion systems

Figure 5 shows a comparison of the power output generated by COGES and other power generation systems that are commonly used as power generators, namely diesel and dual fuel diesel electric (DFDE). To determine the output power of each system in kWh units, the output power calculation is carried out using the equivalent heat input. According to the findings, COGES has a higher output power than diesel or DFDE.

In addition to comparing the output power produced by each system, this research also estimates the carbon emissions produced by each system. Figure 6 shows a comparison of the carbon emissions produced by the COGES system, the diesel system, and the DFDE system. Compared to the diesel system and the DFDE system, the COGES system produces fewer emissions. Each system produces 0.149 $kgCO_2/kWh$, 0.314 $kgCO_2/kWh$, and 0.155 $kgCO_2/kWh$ of carbon emissions, respectively, with the same heat input. The emission estimation in this study is lower than other studies which state that the COGES propulsion system produces carbon emissions of 0.48 kg/kWh (Wiggins, 2011).

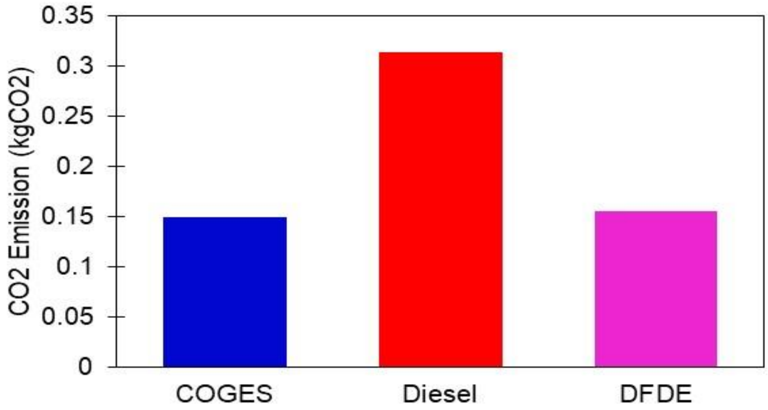

Figure 6 Comparison Graph of Propulsion System Emissions

Apart from the results of CO_2 emissions, the comparison of environmental impacts is obtained using the eco-indicator 99 (H) method. Where the environmental impact will affect health, ecosystem quality, and resources for a power output of 1 kWh. Referring to the input and output of each component in the COGES system, then each component will have an influence on the environment that can be transmitted as an eco-indicator through the life cycle assessment method. Figure 7 shows the environmental impact assessment of the COGES propulsion system. The environmental impact assessment results show four major components that produce high environmental effects, i.e. combustion chamber, gas turbine, heat recovery steam generator, and compressor. The combustion chamber produces an environmental impact of 3.78 mPts/s, this result is consistent with previous research where the environmental impact on the combustion chamber in a gas turbine is 3.92 mPts/s (Budiyanto, Nasruddin, and Nawara, 2020).

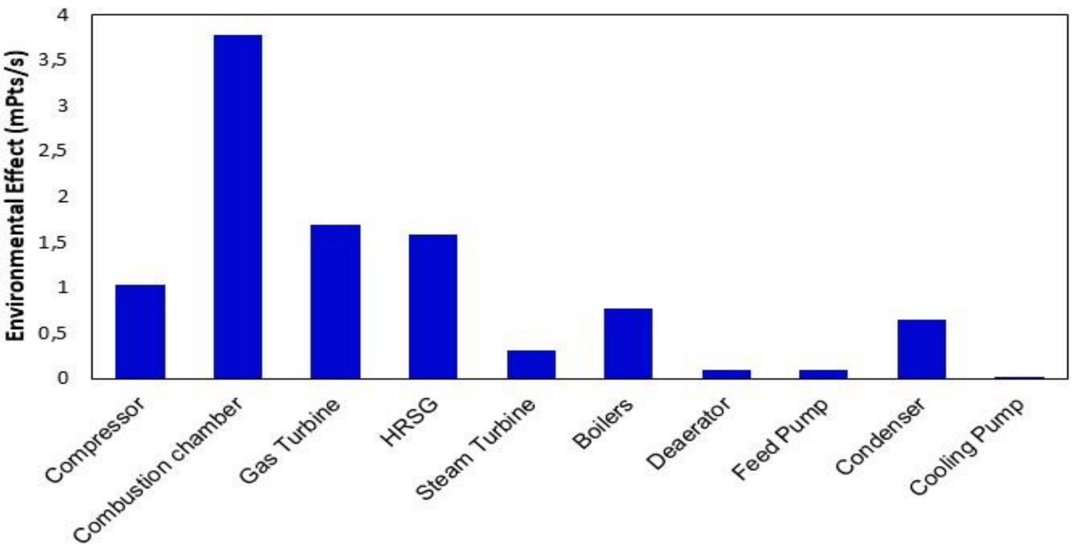

Figure 7 Environmental impact assessment of COGES propulsion system

4. Conclusions

Performance analysis of the COGES propulsion system has been carried out using the method of thermodynamic analysis and environmental impact assessment. The design of a small-scale LNG carrier with a capacity of 7500 m^3 has been used as a case study to determine the desired power requirements. A comparison of the COGES propulsion system with the diesel system and the DFDE propulsion system was also carried out to determine the advantages of the proposed system. The findings of the thermodynamic study indicate that the suggested COGES potentially produce up to 7600 kW of electricity when fully loaded. Only around 24% of the total design load is required for the COGES system to operate at the ship's operational speed of 12 knots, which consumes 1832 kW. The COGES propulsion system has the advantage of higher output power with lower emissions compared to the diesel and DFDE systems. The contribution of carbon emissions to the COGES system, the diesel system, and the DFDE system is 0.149 kgCO_2/kWh, 0.314 kgCO_2/kWh, and 0.155 kgCO_2/kWh, respectively. According to the advantages of the COGES propulsion system, this system is feasible to be proposed as a small-scale LNG carrier propulsion system. It is necessary to carry out further research related to techno-economic studies to assess whether this system is feasible in terms of investment costs.

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List of abbreviations and symbols

COGES = Combination gas-electric steam turbine system
DFDE = Dual fuel diesel-electric
HRSG = Heat recovery steam generator
LNG = Liquefied natural gas
h = enthalpy $(^{kj}/_{kg})$
$h_{ambient}$ = environment enthalpy /ambient $(^{kJ}/_{kg})$
s = entropy environment $(^{kJ}/_{kg.\,K})$
$s_{ambient}$ = environment entropy/ambient $(^{kJ}/_{kg.\,K})$
$\dot{m}$ = mass flow rate $(^{kg}/_{s})$
$T_{ambient}$ = environment temperature /ambient (K)
$\dot{Q}_{in}$ = the calorie input of the system (kW)
$\dot{W}$ = performance output of the system (kW)
$\dot{E}_{x,n}$ = *exergy rate* (kW)

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