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Research Article

# Integrated absorption refrigeration and gas turbine power plant system: Performance enhancement through intake air cooling

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## ABSTRACT

Meeting the world's electricity demands relies significantly on gas turbine power plants; however, extremely hot ambient temperatures can seriously affect these plants. In this study, a gas turbine power plant and an absorption refrigeration cycle for intake air cooling are proposed as a new integrated system. The unique aspect of this setup is that the gas turbine's exhaust gases power the absorption chiller's generator. The chiller's evaporator cools the atmospheric air before entering the compressor. This leads to a reduction in the compressor's work and an enhancement in the power plant's thermal efficiency. The study investigates the impact of inlet air temperature variations on the power generated, energy efficiency, and exergy efficiency of a power plant to reduce greenhouse gas emissions. Also, mathematical modeling and analysis of both Brayton and absorption cycles are reported utilizing EES software. The findings assess that the power generated, energy efficiency, and exergy efficiency enhance considerably as the compressor inlet air temperature drops. The highest net generated power reaches about 61.91 MW at an inlet air temperature of 15°C, while the lowest value of about 57.22 MW is recorded at 50°C. In addition, at 15°C inlet air temperature, the cycle energy efficiency and exergy efficiency are increased by about 8.2% and 50.5%, respectively, compared to 50°C inlet temperature. Therefore, the novelty of the current work is enhancing system efficiency without more fuel consumption.

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## INTRODUCTION

Globally, gas turbines play a vital role in meeting the ever-increasing demand for electricity [1]. They are typically used in combined thermal power plants that rely on natural gas as their primary source of energy [2]. The benefits of gas turbines are manifold, including high efficiency, low emissions, and quick startup time [3]. In addition to power generation, waste heat recovery stands out as another useful application for gas turbine power plants because plenty can be done with the heat wasted during fuel

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combustion— such as steam generation or cooling/heating systems [4, 5]. Yet they face an important challenge: their performance significantly drops under high ambient temperatures [6]. According to Ashley et al. [7], gas turbine efficiency drops by 0.07%, and power output drops by 1.47 MW for every degree rise in the ambient temperature.

To counter this issue, researchers have looked into different methods of cooling the compressor inlet air [8, 9], including evaporative cooling, wet compression, absorption cooling, and mechanical cooling; each technique, though effective, comes with limitations [10]. Evaporative cooling exhibits a small cooling impact compared to other inlet air cooling systems. This limitation becomes particularly noticeable in humid environments when the capacity for cooling is inherently constrained [11]. Still, its capital cost is inexpensive due to the simplicity of the system's components [12]. The indirect evaporative cooling system was considered a potential method for gas turbine inlet air cooling [13]. The gas turbine's efficiency and power production were improved by combining a humidifier with a vapor compression or absorption cooling system. This allowed some input air to chill before mixing it with the main air stream. Wet compression is an operation in which water is sprayed into the intake of the compressor and allowed to evaporate internally, thereby reducing the compressor's demand by a substantial amount. The risk of erosion and corrosion is one drawback of wet compression, potentially increasing maintenance costs and reducing equipment lifespan [14, 15]. An investigation was conducted into combining a fogging system with an Earth-Air Heat Exchanger to create a hybrid system for cooling the air entering gas turbines [16]. The main results showed that the hybrid system increased the yearly average energy production by 9.8%. However, such hybrid systems often involve higher capital costs and increased system complexity.

The latest developed mechanical chiller achieved a Coefficient of Performance (COP) of about 6 [6]. Typically, it generates a significant chilling impact; however, the power needed for operation leads to inefficiencies for the power plant, potentially offsetting the gains from inlet air cooling. On the other hand, absorption chillers only need a small amount of electricity to operate the pumps, but they do not rely on it for their primary function. Nevertheless, there may be challenges with implementing and operating these systems due to their complexity and necessity for a steady heat supply. Furthermore, it is worth noting that double-effect absorption chillers, which are known for their exceptional efficiency, have a COP of approximately 1.5 [6]. The four main parts of an absorption chiller are the evaporator, condenser, generator, and absorber. The absorber mixes the refrigerant and the absorbent, and the generator separates the two, which is where heat is needed. Much less electricity is required to pump the absorbent-rich liquid than would be required for the gas compression of a mechanical chiller. To provide intake air chilling in the combined thermal plant, researchers have developed and implemented absorption chillers. In these chillers, steam was used as the generator's heat source [17]. Boonnasa et al. [18] and Yazdi et al. [19] have investigated various deep integrations with absorption cooling systems. Pourhedayat et al. [20] conducted a recent review paper to compare the various gas turbine intake air pre-cooling strategies, introducing insights into the effectiveness of these cooling strategies under different operating conditions. The significance of heat recovery in combined cycle power plants for increasing electricity production and decreasing fuel consumption was investigated by Popli et al. [21]. Ameri et al. [22] conducted an economic analysis and found that inlet air cooling for gas turbines has an impressive internal rate of return, with a 4.2-year payback. In a basic cycle gas turbine, Sanaye et al. [23] investigated the impact of absorption refrigeration technology in lowering the intake air temperature from 48 to 15°C. The study found that in hot and humid climates, the thermal efficiency of the cycle is 2.7% higher. The payback period for the capital cost is 4.38 years. Moreover, the idea of simultaneously chilling turbine coolant and the inlet air using absorption chillers was explored [6, 24]. The cooling air from the turbine was utilized as a generator's heat source. The evaporator was employed to cool the compressor's intake air, whereas the absorption chiller chilled the turbine coolant. This can either reduce the coolant amount or increase the hot gas temperature while keeping the temperature of turbine blades constant, leading to more power produced [25].

According to the literature, cooling methods have shown the ability to enhance gas turbine performance; however, there remains a need for more efficient and environmentally friendly solutions. The current study proposes a novel integrated system combining a gas turbine power plant with an absorption refrigeration cycle for intake air cooling. In this system, the gas turbine's exhaust gases power the absorption chiller's generator, potentially providing more efficient use of waste heat and addressing some of the limitations of existing cooling methods. One of the critical goals of this method is to reduce the amount of work the compressor has to do while simultaneously increasing the overall efficiency. As a result of this suggested system, an analysis is carried out that analyzes the system's power output, energy efficiency, and exergy efficiency in relation to the various temperatures of the inlet. The results of this investigation provide significant insights into the quality of energy use and viable optimization solutions. The main application of the current works is to maximize the power produced by power plants without consuming more fuel. This will lead to a reduction in greenhouse gas emissions.

## SYSTEM DESCRIPTION

The proposed system under study is shown in Figure 1. It comprises two primary subsystems: (I) a Brayton cycle power plant that generates electricity and (II) an Absorption refrigeration (LiBr cycle) system that provides ambient air

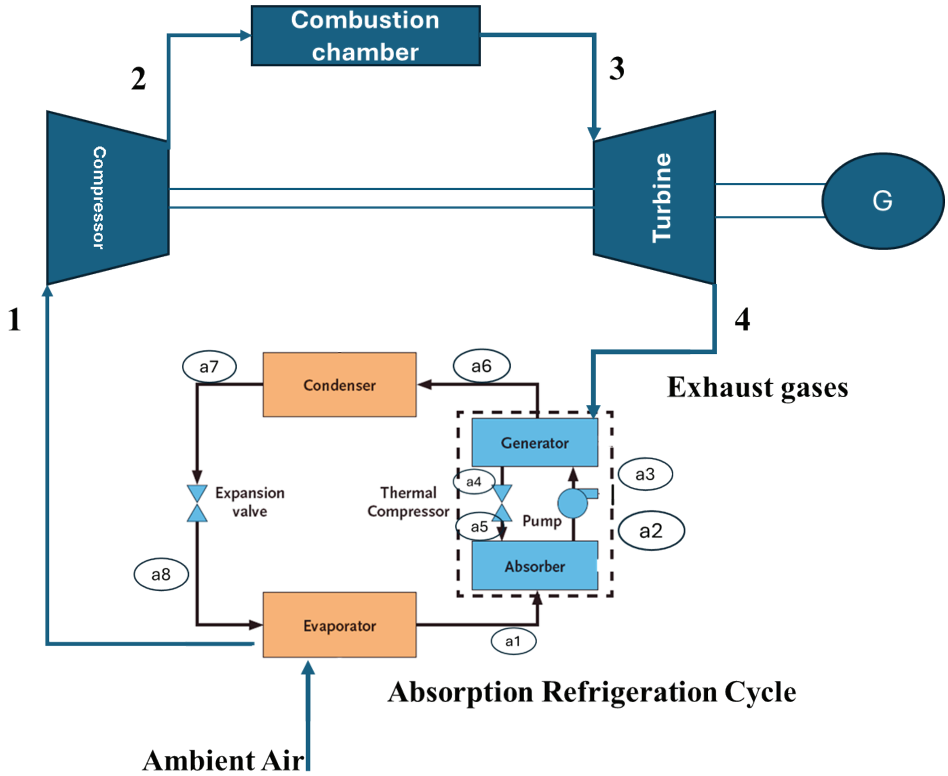


**Figure 1.** Schematic diagram for the proposed cycle.

cooling. Within the first subsystem, the compressor plays its role in compressing air to a certain pressure level before reaching the combustion chamber. The compressed air in the combustion chamber is to be combined with fuel, which raises its temperature while maintaining constant pressure. Finally, the high-pressure and temperature exhaust gas is fed to the gas turbine for power production and electricity generation using an electricity generator.

The other subsystem is used for ambient air cooling prior to the compressor. The ambient air entering the evaporator is to be cooled at constant pressure due to the effect of refrigeration. In this cycle, the turbine's exhaust gases drive the generator unit in the thermal compressor. In the generator, the heat added is used to raise the temperature of the LiBr-water solution, and then the water is vaporized and driven through the pipes to the condenser. The condenser is cooled using ambient air to convert steam back to water. The expansion valve reduces the refrigerant temperature and pressure to chill down the ambient air in the evaporator. The refrigerant converts from liquid to vapour state, which is absorbed by a strong concentration solution. The pump, operated using produced electricity, is used to circulate solution in the cycle.

The current investigation aims to study the effect of intake air temperature by produced power from the power plantm , cycle energy efficiency , and cycle exergy efficiency.

## MATHEMATICAL MODELLING

### Brayton Cycle Analysis

To evaluate the Brayton cycle's performance and maximize energy use, two important factors are its efficiency and exergy analysis. Efficiency is the ratio of useful work production to total energy input, which demonstrates the cycle's ability to transform heat into work. On the other hand, exergy analysis assesses the quality of energy and pinpoints regions of irreversibility and inefficiency in the system. Assessing exergy destruction at each stage reveals potential improvements and optimization opportunities. Efficiency and exergy analysis provide detailed assessments of the Brayton cycle's performance, directing advances in energy conversion technology and sustainable engineering practices [26].

The mathematical expressions which depict these procedures are shown here below [27], [28]:

$$\textbf{Heat added } Q_{in} = \dot{m} \times c_{p,air} \times (T_3 - T_2) \tag{1}$$

$$\textbf{Heat rejected } Q_{out} = \dot{m} \times c_{p,air} \times (T_4 - T_1) \tag{2}$$

**Isentropic process analysis (P2 = P3 and *P4* = *P1*)**

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{P_3}{P_4}\right)^{(k-1)/k} = \frac{T_3}{T_4} \tag{3}$$

$$\textbf{Power}\ \ Power = Q_{in} - Q_{out} \tag{4}$$

$$\textbf{Efficiency}\ \ \eta_I = 1 - \frac{T_1 \times (T_4/T_1 - 1)}{T_2 \times (T_3/T_2 - 1)} \tag{5}$$

$$\textbf{Exergy}\ \ \eta_{II} = 1 - \frac{T_0 \times (T_4/T_0 - 1)}{T_2 \times (T_3/T_2 - 1)} \tag{6}$$

The following table reveals the parameters used in cycle analysis based on the literature.

**Absorption Cycle Analysis**

An integral part of every Brayton cycle, the LiBr-water solution chiller lowers the temperature of the air outside the compressor chamber, hence increasing the cycle's efficiency. It is possible to efficiently extract heat from gas flows by making use of turbine exhaust gases. In EES software, after creating the assumption, the exhaust gas enters the generator section to heat up the LiBr-water solution to separate water from LiBr. The water vapor enters the condenser to convert to water in a liquid phase. This water enters the expansion device to lower its pressure and temperature and cool the air in the evaporator.

Improving the cycle's overall efficiency is possible by lowering the inflow air temperature, which in turn reduces the workload for the compressor. Gas turbine engines are made more environmentally friendly and financially viable by increasing their power output and efficiency using this technology. To maximize energy efficiency and minimize environmental impact, the LiBr-water solution chiller is needed. What follows is an illustration of the equations used to characterize the chiller model (Table 2) [6, 30] :

Where, $m_r$ is the refrigerant flow rate in kg/s, $m_{ws}$ is the weak solution flow rate in kg/s, $m_{ss}$ is the strong solution flow rate in kg/s, $T_E$ is the evaporator temperature, $T_G$ is the generator temperature, and $T_0$ is the reference temperature of 0 °C. Further, the flow chart of the solution process is illustrated in Figure 2. The EES stops calculation when the difference between the assumed and calculated temperatures is less than $10^{-6}$. Flow charts are essential visual tools that simplify complex processes, enhance understanding, facilitate decision-making, and improve communication by providing a clear, step-by-step representation of workflows.

The solution of the current model is conducted firstly by calculating the required compressor power based on the pressure ratio and ambient temperature; the amount of heat added to the combustion chamber is calculated. Finally, the net power is estimated by subtracting compressor power from turbine power. The exhaust gases are used to drive the vapor absorption cycle to cool down the compressor inlet temperature. As mentioned before, the code makes a loop to make the difference between the assumed and calculated temperatures less than $10^{-6}$.

**Table 1.** Current analysis parameters

| Parameters | Symbol | Value |
|---|---|---|
| Air mass flow rate | $\dot{m}$ | 400 kg/s |
| Turbine input temperature | $T_3$ | 727 °C |
| Compressor outlet temperature | $T_2$ | 477 °C |
| Inlet pressure | $P_1$ | 1 bar |
| Compressor and turbine isentropic efficiency [29] | η | 90% |

## RESULTS AND DISCUSSION

After running the Engineering Equations Solver (EES) through a cycle analysis, the key takeaways from the present study are detailed below. Power generation, cycle efficiency (as defined by the first law of thermodynamics), and exergy efficiency (as defined by the second law of thermodynamics) are the main foci of this investigation.

The assumption used in EES simulation is illustrated as follows:

- Steady-state operation without including the pressure drop.
- Constant specific heat and isentropic efficiency.
- Heat exchanger efficiency 85%.

**Effect of Inlet Temperature on Power**

The cycle parameters, such as the combustion chamber and turbine input temperatures, remain constant to

**Table 2.** Illustration of the equations used to characterize the chiller model

| | | |
|---|---|---|
| **Evaporator balance** | $Q_E(kW) = m_r \times (h_{Evap,out} - h_{Evap,in})$<br>$Q_E(kW) = m^{\cdot} \times c_{p,air} \times (T_3 - T_2) \times \eta_{HX}$ | (7) |
| **Generator balance** | $Q_G(kW) = m_{ss}h_{to\ absorber} + m_r h_{to\ condenser} - m_{ws}h_{from\ absorber}$ | (8) |
| **Cycle COP** | $COP_{AS,act} = \frac{Q_E}{Q_G}$ | (9) |
| **Cycle Exergy** | $\zeta_{II} = \frac{COP_{AS,act}}{COP_{AS,ideal}} = \left(\frac{Q_E}{Q_G}\right)\left(\frac{T_O - T_E}{T_E}\right)\left(\frac{T_G}{T_G - T_O}\right)$ | (10) |

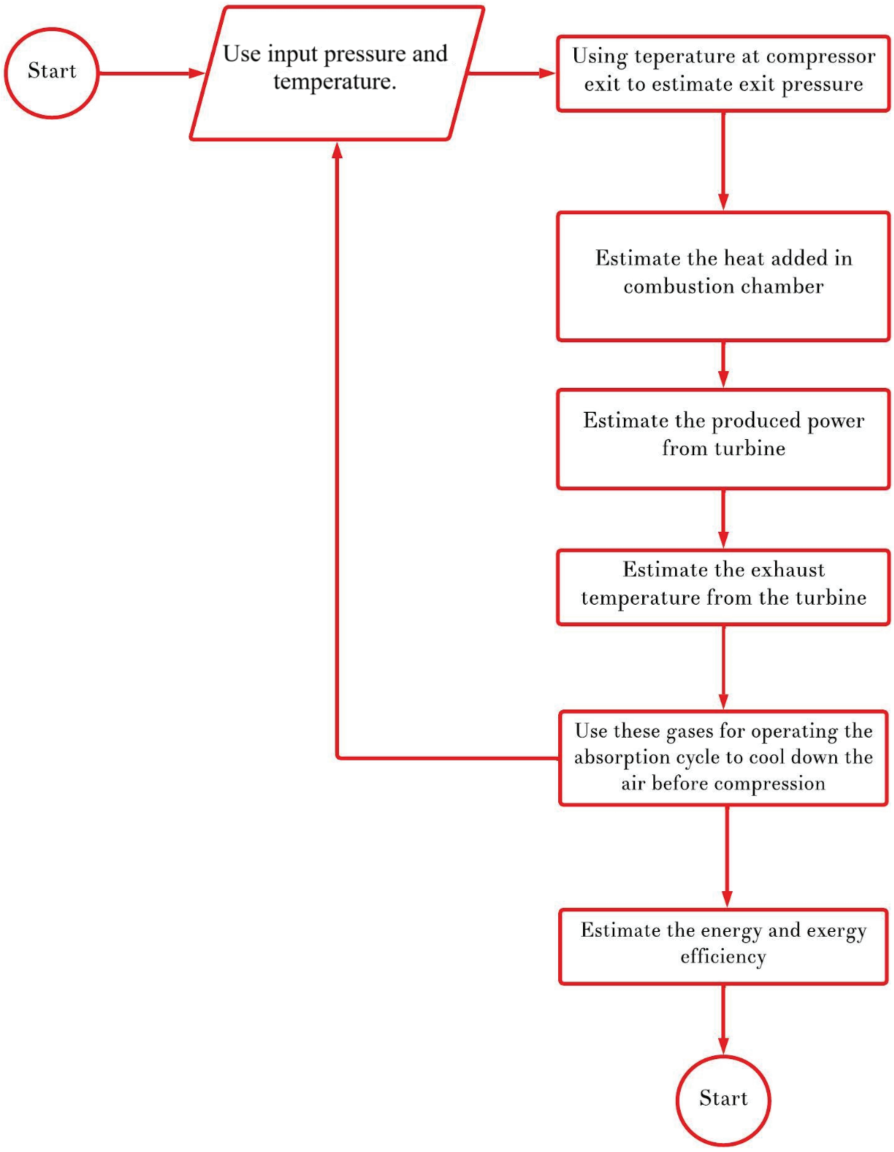


**Figure 2.** Flow chart of the mathematical methodology

estimate the net output power correctly. Figure 3 demonstrates the impact of compressor intake temperature on the net output power. As shown in this figure, the output power improved as the inlet temperature decreased due to the cooling effect of the absorption chiller. Therefore, the reduction in temperature has a positive impact on output power. The maximum value is 61.91 MW obtained at 15$^o$C, and the lowest value is 57.22 MW at 50$^o$C, as indicated in the figure.

**Effect of Inlet Temperature on System Efficiency and Exergy**

The second main concern is estimating the system efficiency according to the first law of thermodynamics. Figure 3 illustrates the impact of compressor intake temperature on the cycle efficiency. As mentioned before, the power increases with a reduction in the temperature with the constant heat input because of constant parameters, as mentioned in Table 1. The improvement in power led to an improvement in cycle efficiency because the input heat is constant. Figure 4 shows that the improvement of cycle efficiency results from temperature reduction. The maximum value is 61.6 % obtained at 15$^o$C, and the lowest value is 56.93 % at 50$^o$C, as indicated in the figure.

The second main concern is estimating the system exergy according to the second law of thermodynamics. Figure 4 illustrates the impact of compressor intake temperature on the cycle exergy. As mentioned before, the power increases with a reduction in the temperature with the constant heat input because of constant parameters, as mentioned in Table 1. The improvement in power led to an improvement in cycle exergy because the input heat

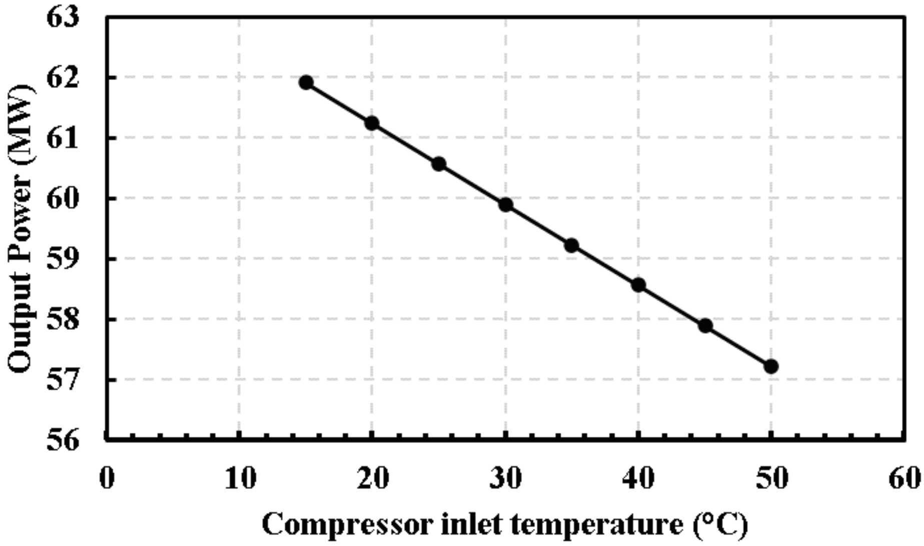


**Figure 3.** Impact of compressor input temperature on net output power.

is constant. Figure 5 shows that the improvement of cycle exergy results from temperature reduction. The maximum value is 55.66 % obtained at 15°C, and the lowest value is 36.99 % at 50°C, as indicated in the figure.

As indicated in these figures, exergy efficiency is lower than energy efficiency as energy efficiency measures the overall usefulness of energy, including both high-quality and low-quality forms of energy. In contrast, exergy specifically considers the highest-quality energy available within a system. The absorption cooling system enhances the power output and efficiency of gas turbines by lowering the temperature of the air that enters the compressor. This is especially beneficial in hot areas, where high ambient temperatures usually lead to a decrease in performance. The colder and more compact incoming air decreases the energy needed by the compressor, enabling a more significant amount of air to pass through and potentially achieving higher pressure ratios. As a result, there is an enhancement in the efficiency of the cycle and a rise in the capacity for power generation.

**Effect of COP on System Efficiency**

On the one hand, the COP of the absorption refrigeration cycle directly impacts how effectively it can cool the inlet air of the Brayton cycle compressor. A higher COP means more efficient cooling, which leads to cooler air entering the compressor. Figure 6 shows the effect of the

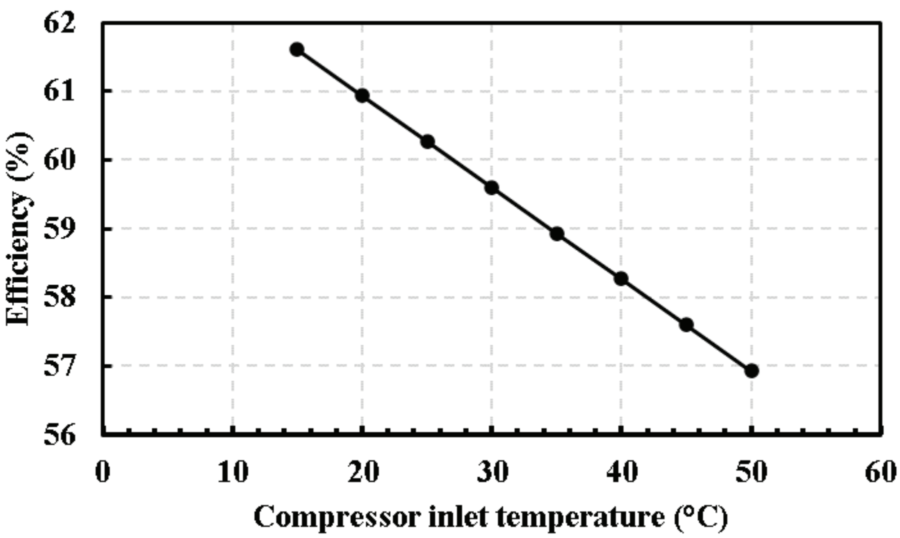


**Figure 4.** Impact of compressor input temperature on system efficiency.

COP on the cycle efficiency. As shown in this figure, as the COP increased, the efficiency increased.

On the other hand, the energy (COP) efficiency and exergy efficiency of the absorption cycle remain constant during the analysis because of the constant generator temperature and constant evaporator temperature. The results showed that the COP of the absorption cycle is 0.899 and the exergy efficiency is 0.3615, respectively.

**Literature Review Comparison**

The performance of the current study, especially intake air cooling systems in gas turbine power plants, has been highly improved by combining absorption refrigeration equipment. The maximum net power we reproduced in the current study was 61.91 MW, and this was the inlet air temperature of 15 °C, and when the air inlet temperature was 50°C, only ~57.22 MW reached the grid. This conclusion is in agreement with the results obtained by Shukla and Singh [31], which explain that lower inlet temperatures are beneficial for gas turbine performance since increases in air density and mass flow rates, as well as better combustion, can be reached, hence, positivism in power output.

At 15°C and compared to 50°C working conditions, an 8.2% and 50.5% increase in cycle energy efficiency and exergy

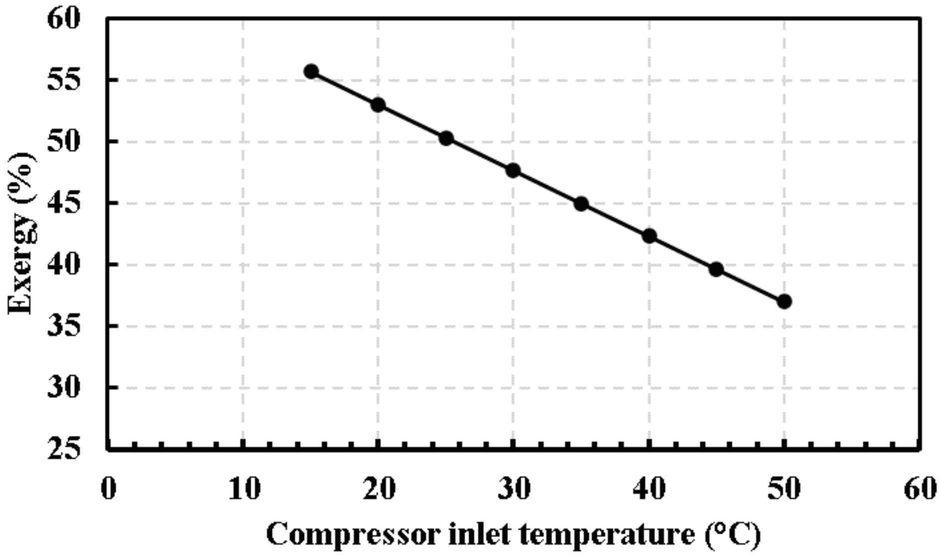


**Figure 5.** Impact of compressor input temperature on system exergy.

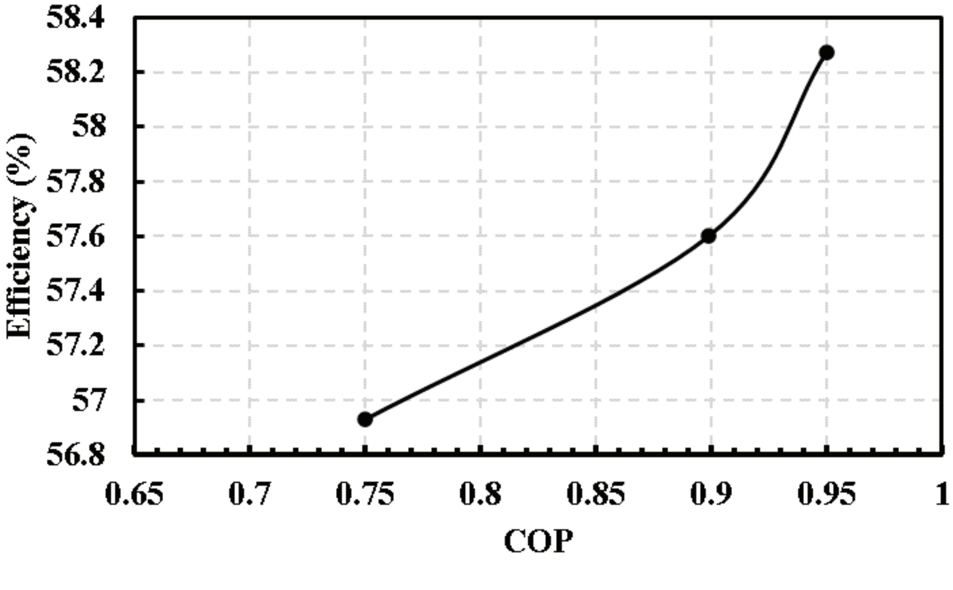


**Figure 6.** Impact of COP on system efficiency.

efficiency was observed. These findings are also compatible with those of Elberry et al. [8], who illustrated that employing waste heat to improve energy and exergy efficiencies with the application of a lithium bromide-water absorption cooling unit in a gas turbine combined cycle is beneficial. These studies speak to the significance of increasing the inner performance of heat and power plants by optimizing the inlet air temperature, which provides an interesting direction for the further growth of energy systems.

## CONCLUSION

This study successfully achieved its objective of enhancing the efficiency of a gas turbine power plant by integrating it with an absorption refrigeration cycle to cool the inlet air using exhaust gases. The results demonstrated that reducing the compressor inlet air temperature significantly boosts the plant's performance. The highest values recorded were 61.91 MW, 61.6%, and 55.66%, respectively, when the inlet temperature was 15°C. The concept lies in utilizing waste heat to cool the inlet, hence enhancing power generation, efficiency, and sustainable practices. Future work can investigate other combinations, maximize integration, and conduct environmental and economic studies. The study's limitations are in Table 1 and the assumption.

The authors recommended that future work conduct a complete economic analysis, including the levelized cost of energy, payback period, and rate of return.

## AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## ETHICS

There are no ethical issues with the publication of this manuscript.

## STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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