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Thermodynamic Analysis and Multi-Objective Optimization of Binary Geothermal Power Plant Using CO_2 as Working Fluid with Genetic Algorithm Principles

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Abstract: The future of geothermal energy is increasingly linked to the development of Enhanced Geothermal Systems (EGS) technology, which promises to become a substantial renewable energy source. However, low heat recovery factors and water constraints hinder its widespread adoption. A promising solution to overcome water limitations is the utilization of CO_2 as a working fluid in binary geothermal power plants, leveraging its lower boiling point to improve energy extraction efficiency. This research explores using CO_2 to address these challenges as a working fluid in binary geothermal power plants to avoid water constraints, leveraging its lower boiling point to enhance energy extraction efficiency. A comprehensive thermodynamic and thermoeconomic analysis was conducted, focusing on the impact of temperature, pressure, and mass flow rate on the plant's exergetic efficiency, which represents the ability of the system to convert heat to valuable work and exergoeconomic performance that represents the economic consideration from energy produced with the parameter needs. Genetic algorithms are employed to optimize these parameters, a computational method inspired by natural selection that helps identify optimal solutions across a Pareto front, highlighting trade-offs between goals from multi-objective parameters. The Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) was then used to determine the most favorable operating conditions. The results indicate that optimal conditions for CO_2 are 140°C, 19,950 kPa, and 100.95 kg/s, achieving an energy efficiency of 30% and an exergoeconomic value of 0.14 \$/s. These findings significantly advance the field by enhancing both the performance and economic viability of geothermal power plants, providing valuable insights for promoting sustainable energy solutions and mitigating environmental impacts. These research outcomes guide the optimal parameters to achieve the most optimal energy produced on the geothermal power plant by using CO_2 as the working fluid.

Keywords: CO_2 Utilization; Geothermal Power Plant; Binary Cycle; Exergy; Exergoeconomic; Multi-Objective Optimization

1. Introduction

Climate change, driven by rising levels of atmospheric carbon dioxide (CO_2), presents a critical challenge to global environmental sustainability[1–3]. As CO_2 concentrations continue to increase, there is an urgent need to transform this potent greenhouse gas from a harmful pollutant into a valuable resource[4,5]. This transition is vital not only for decreasing worldwide emissions but also for pushing innovative technologies that promote environmental sustainability. CO_2 utilization technologies offer a dual benefit by not only reducing emissions but also repurposing CO_2 for various industrial applications, such as carbon capture and utilization (CCU) and enhanced oil recovery (EOR)[6,7].

The importance of embracing CO_2 utilization practices emphasizes their critical contribution to the worldwide initiative to address climate change and move towards a more sustainable and resilient future[8,9]. The significance of adopting CO_2 usage strategies underscores their vital role in the global effort to combat climate change and transition towards a more sustainable and resilient future[10]. This paper discusses two complex issues: the environment and renewable energy. The environmental concern is greenhouse gas (GHG) abatement, while the renewable energy concern is enhancing the quality of geothermal energy. The existing geothermal power plants utilizing water as the working fluid have several drawbacks, such as relatively low energy conversion efficiency, high demand for water for both operation and cooling process, which can strain water resources in the area, and susceptibility to corrosion[11,12]. Additionally, geothermal plants using water as the working fluid can produce greenhouse gas emissions such as H_2S, whereas utilizing CO_2 obtained from carbon capture and storage (CCS) can provide environmental benefits by reducing the amount of CO_2 in the atmosphere. This research proposes strategies for addressing both challenges at the same time, utilizing geothermal to reduce GHG emissions while fulfilling the energy demand.

The utilization of CO_2, particularly in innovative applications such as geothermal power generation for enhanced geothermal systems (EGS), represents a significant advance in addressing these challenges[13–15]. The use of CO_2 as a working fluid for geothermal extraction and carbon storage in the Enhanced Geothermal System (EGS) has been the subject of several prior studies; however, no work has been done that makes use of geothermal heat with low to medium enthalpy. Traditional geothermal systems typically employ water or steam as the working fluid, but recent studies suggest that utilizing CO_2 can substantially improve the efficiency of these systems[16–18]. The lower boiling point of CO_2 compared to water allows it to absorb and vaporize heat more effectively, which drives turbines for electricity generation with greater efficiency[19,20]. This innovative approach not only enhances the energy conversion rates but also offers a pathway for the geological storage of CO_2, thereby contributing to carbon sequestration efforts[21–23]. The attractive properties of CO_2 make it an attractive fluid change in geothermal systems.

CO_2 has been considered a geothermal working fluid because of its superior thermodynamic characteristics when compared to water-based systems, offering an opportunity to store it geologically. Thermodynamic analyses, which evaluated operational factors like temperature, pressure, and mass flow rate, demonstrated this[24,25]. The reported studies demonstrate the improved effectiveness, energy efficiency, and cost-effectiveness of systems based on CO_2. These systems are considered a promising solution for sustainable and efficient geothermal power generation. They also have the potential to create clean energy alternatives[26,27]. The research, similar to Xu et al.'s study, investigated the integration of a solar thermally enhanced geothermal system with CO_2 to address low-pressure requirements[28]. Multiple reservoirs improved the system's performance while eliminating the need for recompression compressors. In addition, Quall et al. investigated SF6–CO_2 mixtures for geothermal power plants, employing a Newton–Raphson method[29]. Optimal efficiencies were achieved with 15% and 20%, highlighting the potential for enhanced cycle performance. The study also assessed the effects on thermal efficiency and heat exchanger sizing. Increased well diameters play a crucial role in significantly boosting geothermal power production. Furthermore, O. Saar et al. found that CO_2 was superior in sedimentary geothermal reservoirs due to its lower pressure losses compared to brine[30,31]. CO_2 is more efficient in generating power at lesser depths and lower permeabilities, making it a superior choice as a working fluid in secondary Rankine cycles compared to R245fa[32].

Many of the reported studies focused on modifying the geothermal power plant system. Numerous geothermal power plant systems in the industry use a variety of configurations, including single flash, double flash, binary, combined cycle, and dry steam systems[33,34]. Therefore, we need to implement numerous modifications to the current system[35,36]. We present the potential of low to medium-geothermal reservoirs for power generation to replace the conventional working fluid with CO_2. This research focuses on optimizing the binary geothermal system using carbon dioxide as the working fluid. The binary system, which typically uses a secondary fluid with a lower boiling point than water, can benefit significantly from the unique properties of CO_2. This study analyses several operational variables, such as temperature, pressure, and mass flow rate, to determine their impact on the system's performance through comprehensive thermodynamic analysis. Key performance indicators, including efficiency, exergy, irreversibility, and operating costs, are evaluated.

This study aims to get a comprehensive knowledge of the operational factors that influence the efficiency of a binary geothermal system using CO_2 to enhance its appeal for low- and medium-enthalpy geothermal power plants. In addition, the findings are expected to be a critical resource in the decision-making process to improve the performance of the geothermal cycle system. This study highlights the significance of sustainable energy solutions and identifies CO_2 as an attractive option for advancing geothermal energy production. The research on carbon capture has typically concentrated on CO_2 utilization rather than CO_2 storage, such as geothermal energy extraction. However, achieving both simultaneously is innovative for today's technology. The potential of low to medium enthalpy geothermal energy for power production is presented in this paper. These benefits of CO_2 in low- to medium-enthalpy geothermal reservoirs make it a viable option for lowering CO_2 emissions and making use of low- to medium- enthalpy geothermal potential. It means that utilizing CO_2 as the working fluid has the potential to unlock possibilities for exploiting geothermal resources that are currently considered unprofitable or of little benefit using conventional water-based methods. It has the potential to facilitate the development of novel geothermal projects in previously unsuitable regions, therefore expanding the geographical scope and capacity of geothermal energy. Next, in this research Section 2 explains the methodology used for parametric and optimization investigations. Section 3 shows the result and discussion of the Parametric Study of Binary Cycle Geothermal and Exergy Destruction Analysis of Each Component. Finally, Section 4 summarizes the integration of binary geothermal plants with CO_2 as the working fluid for addressing CO_2 emissions in the context of geothermal energy production.

2. Methodology

The geothermal plant utilizes the medium enthalpy of brine in a binary cycle that involves two fluids: the primary fluid, brine, travels to a heat exchanger where it exchanges heat with the secondary fluid, CO_2. Next, first and second law analyses are analysed to identify major loss components. MATLAB software is used for parametric and optimization investigations, with fluid characteristics obtained from REFPROP. The custom scripts were written in MATLAB to perform the necessary thermodynamic calculations, including those related to heat transfer, work output, and efficiency of the system. To calculate all the parameters, the fluid properties from REFPROP were incorporated into the MATLAB simulations using the REFPROP MATLAB wrapper. This integration allowed for accurate thermodynamic property data of CO_2, such as enthalpy and entropy to be utilized directly within the MATLAB environment. The REFPROP data was crucial for ensuring the accuracy of the thermodynamic assessments and for modeling the behavior of CO_2 under various operating conditions. Finally, the optimization is undertaken using the optimization toolbox with gamultiobj Algorithm. This algorithm was utilized in this study for performing multi-objective optimization of the binary geothermal plant using CO_2 as the working fluid. This algorithm is based on genetic algorithms (GA), which are particularly well-suited for solving optimization problems involving multiple conflicting objectives.

Some assumptions are undertaken during the study: steady state, neglecting kinetic/potential energy, CO_2 condenses in the condenser with controlled mass flow, ignoring pressure/heat losses. The steady state assumption and neglecting kinetic and potential energy aligns with thermodynamic evaluation study findings[37–40]. Moreover, geothermal power plants function as base load power generators that operate continuously with only minor fluctuations in their operating parameters. The primary focus of the study is on heat transfer and work output, which are predominantly influenced by thermal energy rather than kinetic or potential energy. Therefore, ignoring these components simplifies the analysis while maintaining its accuracy and relevance to the study's objectives. Figure 1 depicts the CO_2-based binary geothermal plant. In a CO_2-based binary geothermal power plant, the innovative design optimizes energy conversion by employing carbon dioxide (CO_2) as the primary operational fluid in a binary cycle configuration. The process initiates with geothermal brine, sourced from the Earth's reservoirs, which serves as the initial heat carrier. The brine will travel to the heat exchanger, where its thermal energy is effectively transferred to the circulating CO_2 fluid in a distinct loop. Due to its lower boiling point, CO_2 easily absorbs and vaporizes heat, transforming into a high-pressure gas that allows for efficient power production.

This high-pressure CO_2 vapor is then sent into a turbine, where it expands and drives the turbine blades to produce power. The vapor is condensed back into a liquid state after going through the turbine. The process is recommenced by returning the condensed working fluid to the heat exchanger. Table 1 describes the detailed parameters of this CO_2 binary cycle geothermal power plant.

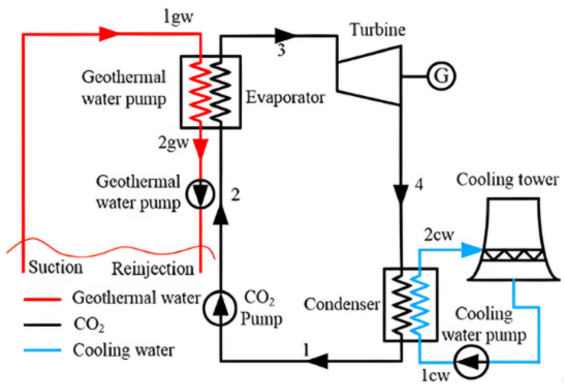

Fig. 1: Binary Cycle Geothermal Power Plant's Schematic Representation[31].

Under design conditions, the temperature and flow of mass' rate of geothermal water are established at 140°C and 100 kg/s, respectively[31,41]. Geothermal water pressure is 1.5 MPa (1500 kPa), while the temperature of water reinjection into geothermal is fixed at 85°C. Following this, the energy analysis, based on the first law for an open system, proceeds as follows:

$$\frac{dE_{cv}}{dt} = Q - W + \sum_i \dot{m}_i \left(h_i + \frac{v_i^2}{2} + gZ_i\right) - \sum_o \dot{m}_o \left(h_o + \frac{v_o^2}{2} + gZ_o\right) \quad (1)$$

The subscriptions of i and o denote the inlet and outlet states. Q and W stand for net heat and work input, while $\dot{m}$, v, and Z represent mass flow rate, velocity, and height.

For the fluid's properties, h signifies the enthalpy, while s denotes the entropy. Table 2 summarizes the detailed energy analysis. Once the energy calculations are complete, the exergy analysis is performed for each state using equation (2). Exergy calculations are carried out by determining the reference state temperature of 25°C and pressure of 101.3 kPa. Physical exergy calculations as in equation (2) are carried out where enthalpy and entropy are obtained from REFPROP. Exergy rate calculation provide a method to determine both the exergetic efficiency and exergy destruction for individual components using the following equations:

$$Ex = \dot{m}(h_1 - h_0) - T_0(S - S_0) \quad (2)$$

The subscription of 1 and 0 refer to the state of the component and the ambient state. Exergy destruction is determined by evaluating the difference in exergy values before and after each component, taking into account the irreversibilities in the system, such as friction and heat loss. The difference between the exergy input and output is used as an indicator of the inefficiency found within the system. The exergy destruction, $\dot{E}_{D,k}$, can be obtained using the following equation:

$$\dot{E}_{D,k} = \Sigma\dot{E}_{fuel} - \Sigma\dot{E}_{product} \quad (3)$$

The fuel, $\Sigma\dot{E}_{fuel}$, of a component is determined by the total exergy inflows to it, whereas the product, $\Sigma\dot{E}_{product}$, is determined by the total exergy discharges from it. For each component of the geothermal system, the exergy destruction can be obtained using the equation in Table 3.

The comparison between the estimated energy output (product) and the potential exergy used is referred to as exergetic efficiency, η_{Ex}, as shown in the following equation:

$$\eta_{Ex} = \frac{\Sigma\dot{E}_{product}}{\Sigma\dot{E}_{fuel}} \quad (4)$$

Table 1. Operating Parameter for CO_2 Binary Cycle Geothermal Power Plant[1).

Parameter	Values
P (MPa)	0.101325
$\dot{m}$gw (kg/s)	100
Pgw (MPa)	1.5
T1gw (°C)	140
T2gw (°C)	85
Pcw (MPa)	0.3
T1cw (°C)	15
Ptur,in (MPa)	12-20
Ttur,in (°C)	120-140
ηtur	0.8
ηpump	0.8
ηgen	0.98
Hpump,gw (m)	10
Hpump,cw (m)	20

Table 2. Calculation of energy balance for each component.

Component	Energy balance
Reservoir	$Q_{in} = \dot{m}_{1gw}\,(h_1)$
Evaporator	$\dot{m}_{1gw}(h_{1gw} - h_{2gw}) = \dot{m}_2(h_3 - h_2)$
Condenser	$\dot{m}_4(h_4 - h_1) = \dot{m}_{1cw}(h_{2cw} - h_{1cw})$
Turbine	$\dot{W}_T = \dot{m}_3(h_3 - h_4)$
Pump GW	$\dot{W}_{Pgw} = \dot{m}_{2gw}\,(h_{3gw} - h_{2gw})$
Pump CO_2	$\dot{W}_{Pco2} = \dot{m}_1\,(h_2 - h_1)$
Pump CW	$\dot{W}_{Pcw} = \dot{m}_{3cw}\,(h_{1cw} - h_{3cw})$

Table 3. Exergy Destruction of Each Component.

Component	Exergy Destruction
Evaporator	$\dot{E}_{D,evap} = (\dot{E}_{1gw} + \dot{E}_2) - (\dot{E}_{2gw} + \dot{E}_3)$
Turbine	$\dot{E}_{D,t} = \dot{E}_3 - (\dot{E}_4 + \dot{W}_t)$
Condensor	$\dot{E}_{D,Cond} = (\dot{E}_4 + \dot{E}_{1cw}) - (\dot{E}_1 + \dot{E}_{2cw})$
CO_2 Pump	$\dot{E}_{D,CO_2Pump} = (\dot{E}_1 + \dot{W}_p) - \dot{E}_2$
Cooling Water Pump	$\dot{E}_{D,WP} = (\dot{E}_{CT} + \dot{W}_p) - \dot{E}_{1cw}$
Geothermal Water Pump	$\dot{E}_{D,GWP} = (\dot{E}_{2gw} + \dot{W}_p) - \dot{E}_{GWP}$

Economic system analysis is required to analyze the feasibility of a plant. This analysis includes purchased and installation equipment costs, operation and maintenance (O&M) costs, and energy used while the plant is operating. Exergoeconomic analysis, also known as thermoeconomic analysis, is a study that applies economic concepts to analyze the exergy analysis of a given system. The thermoeconomic analysis is conducted by using the cost balance equation on the system components. In exergoeconomic analysis, the exergy value that has been determined before will be used as the cost rate. Table 4 outlines the cost balance for each component, considering the component's fuel exergy and product exergy, denoted as Ċeq. As previously stated, it combines both the costs associated with the fuel rate of exergy and the capital investment required for any of the components included in the product rate of exergy. The equilibrium of the total system's cost rate is found by conducting an economic analysis, which is represented as a function of fuel costs, as well as operating and maintenance costs. This relationship is expressed in the following equation:

$$\dot{C}_{total} = \dot{C}_{fuel} + \Sigma_{eq}(\dot{Z}_{eq} + \dot{Z}_{O\&M}) \quad (5)$$

where $\dot{C}_{total}$ is the total of the product price and $\dot{C}_{fuel}$ is the total price of fuel. $\dot{Z}_{eq}$ represents the cost rate of the equipment. Then, $\dot{Z}_{O\&M}$ indicates the operation and maintenance cost rate. This term generally refers to the yearly cost of capital (usually calculated using the Capital

Recovery Factor) associated with each individual equipment or component. This term refers to the cost rate related to the operation and maintenance of any individual equipment or component inside the system. The cumulative costs for operation and maintenance can be calculated utilizing the subsequent equation:

$$\left(\dot{Z}_{eq} + \dot{Z}_{O\&M}\right) = \frac{\dot{Z}_{eq}\ x\ \phi}{h\ x\ 3600}\text{CRF} \quad (6)$$

In this context, ϕ symbolizes the maintenance factor, while h signifies the operating time in hours. The Capital Recovery Factor (CRF) is a mathematical factor used to modify the present value of payments over a specific period of time, taking into account of the interest rate. The CRF may be calculated using the variables i (rate of interest) and n (number of periods). The Capital Recovery Factor (CRF) is a quantitative measure used to determine the yearly expense of an investment, taking into account the initial capital expenses, the interest rate, and the duration of the investment. It plays a vital role in calculating the expenses related to the loss of available energy in a system, which is critical for recognizing and reducing inefficiencies. The average general interest rate for the whole economic life of the plant is considered to be 3%, as shown in Table 5.

$$\text{CRF} = \frac{i(1+i)n}{(1+i)n-1} \quad (7)$$

Zeq denotes the component rate of cost associated with capital investment, operation, and maintenance in this context. Table 5 describes the essential parameters for economic assessment, encompassing the interest rate, maintenance factor, and lifespan, which are determined based on the economic conditions of a country.

Table 4. Exergoeconomic Balance Equation for All Components.

Component	Cost Balance
Evaporator	$\dot{C}2_{gw} + \dot{C}3 = \dot{C}1_{gw} + \dot{C}2 + \text{Z}_{\text{evaporator}}$
Pump_{gw}	$\dot{C}3_{gw} = \dot{C}2_{gw} + \dot{Z}_{pump}$
Pump CO_2	$\dot{C}2 = \dot{C}1 + \dot{Z}_{pump}$
Pump_{cw}	$\dot{C}1_{cw} = \dot{C}3_{cw} + \dot{Z}_{pump}$
Condenser	$\dot{C}1 + \dot{C}2_{cw} = \dot{C}4 + \dot{C}1_{cw} + \dot{Z}_{\text{condenser}}$
Turbine	$\dot{C}4 = \dot{C}3 + \dot{Z}_{\text{turbine}}$

Table 5. Exergoeconomic Parameters.

Parameter	Value
Annual operation hours	7000 h
Lifetime of system	25 years
Annual interest rate	3%
Maintenance factor	1.06

Parametric analysis was carried out to see the effect of operating parameters of temperature, flow rate, and turbine pressure on the efficiency of the geothermal plant which was carried out using MATLAB and REFPROP for the fluid properties used. The parameters are systematically changed within a set range, based on the realistic operational constraints. The temperature of the turbine is adjusted from 120-140°C, the pressure is 12,000-20,000 kPa and the flow rate is 70-110 kg/s. Thermodynamic models are used to evaluate the impact of these modifications on important performance metrics, including energy efficiency, irreversibility, and exergetic efficiency. Once the thermodynamic evaluation has been comprehensively reviewed by this sensitivity study, the research will move into the optimization phase. During this stage, the results of the sensitivity analysis will direct the optimization procedure, taking into account both performance metrics and economic expenses to achieve the most efficient and cost-effective functioning of the system. This technique allows for the identification of the most crucial characteristics that affect system optimization and serves as a foundation for suggesting methods to improve system performance and reduce economic risks.

3. Result and Discussion

3.1 Binary Cycle Geothermal Power Plant

There are five main components in the binary geothermal system including evaporator, pump, condenser, turbine, and cooling tower using a reservoir as a heat source with a 140°C of temperature and a mass flow rate of 100 kg/s. A detailed analysis of the system's performance, as presented in Table 6, includes the energy and exergy characteristics of each state within the cycle. These values were calculated using specific thermodynamic equations (eq. 1 and 2), providing a comprehensive understanding of the energy transformations occurring throughout the system. The Condenser Cooling Tower (CT) has the greatest energy value, with a substantial energy transfer rate of 61,820 kW. This is attributed to a high mass flow rate of 643.49 kg/s and an enthalpy of 63.27 kJ/kg in the cooling water. The flow rate of the inlet and outlet of the cooling tower component in this study is quite lower than that of a single-flash or double-flash geothermal plant system. This is because the single flash system requires a greater flow rate to condense steam, which can increase the volume and speed of steam to manage the higher thermal output[42). This implies that the cooling water system has a crucial function in controlling the heat output of the plant. Conversely, the CO_2 pump and turbine, essential components of the CO_2 cycle, have lower energy values, suggesting that their primary function is energy conversion rather than energy transmission.

Next, the second largest energy value is the evaporator. The energy value of this component is 56,307 kW, indicating its excellent energy absorption capability. The exergy value corresponding to the given situation is

29,466 kW, indicating a significant potential for converting a substantial portion of the energy transported in the evaporator into usable work. The high exergy of the evaporator highlights its ability to efficiently capture thermal energy from the geothermal source. This is crucial for the entire energy conversion process of the plant.

The turbine, which utilizes the expansion of compressed CO_2 to transform thermal energy into mechanical energy, often for power generation, exhibits an energy output of 52,042 kW. This signifies the quantity of energy that may be used for the transformation into mechanical work, driven by the decrease in enthalpy as the CO_2 expands via the turbine. The exergy value at the turbine is 24,194 kW, representing the greatest potential work that can be obtained from the CO_2 steam under perfect conditions. This significant number indicates the existence of irreversibilities and underscores the possibility for more improvement in turbine operation to harness more of this exploitable energy. The binary cycle geothermal power plant system achieves an overall work output of 2011.961 kW. Despite its impressive work output, the energy efficiency of the binary cycle is recorded at 8.64%. This result is aligned with the previous study, which also evaluated the basic CO_2 transcritical power cycle for low geothermal plant[43].

3.2 Parametric Study of Binary Cycle Geothermal Turbine Inlet Pressure

To ascertain the ideal outlet pressure value from the evaporator within the range of 12000 kPa to 20000 kPa, a parametric investigation for turbine inlet pressure is conducted, incorporating the optimal variables of the flow rate of mass of CO_2 and temperature at the inlet of the turbine. Figure 2 shows a modest rise in overall expenses along with the increase in pressure due to the increased power required to increase the pressure, which necessitates fuel consumption. The energy efficiency evaluation decreases as the pressure climbs from the highest to the lowest, 24.40% and 3.45%, respectively. When the turbine intake pressure rises, the temperature of the incoming fluid generally drops, as seen in Fig. 2, assuming a constant mass flow rate. The drop in temperature is a result of the pressure-temperature interaction. When pressure increases, the specific volume decreases, leading to a fall in specific enthalpy. This ultimately affects the overall energy efficiency of the system[44]. The parametric analysis study is comparable to the one conducted by Wu et al., who performed a parametric analysis on CDTPC (CO_2 transcritical power cycle) turbine inlet. They found that the energy efficiency reaches its highest value of 8.2% when the incoming turbine pressure reaches 17,500 kPa[43]. The congruity of these findings suggests that the parametric analysis was accurate since it aligns with previous research.

Next, the red diamonds indicate the exergetic efficiency of the system. Unlike energy efficiency, exergetic efficiency demonstrates a slightly increasing trend with increasing pressure. Starting at around 18% at 12,000 kPa, the exergetic efficiency gradually rises to about 6.78% as the pressure reaches 20,000 kPa. This indicates that, although the energy efficiency decreases with higher pressures, the system's overall exergy utilization improves marginally. Exergetic efficiency measures how well the system utilizes the available exergy, accounting for both the useful work produced and the irreversibilities within the system. The small rise in exergetic efficiency at higher pressures suggests that there may be a sweet spot where the system balances energy conversion efficiency with efficient exergy utilization. As pressures rise, more and more exergy are lost.

Then, the total exergy destruction escalates with rising pressure. Specifically, it elevates from 0.0065 kW to 4684.89 kW due to diminished turbine work and heightened exergy destruction. This increasing trend of exergy destruction indicates that higher pressures lead to greater irreversibilities within the system, contributing to a loss of useful exergy and thus reducing the overall efficiency. The decline in turbine work stems from an upsurge in turbine inlet pressure, resulting in decreased enthalpy and entropy values. The comparative graph illustrates the complex interplay between turbine inlet pressure, energy efficiency, exergetic efficiency, and exergy destruction in a binary geothermal power plant using CO_2 as the working fluid. The insights gained from this analysis are crucial for optimizing the system's design and operation, aiming to enhance efficiency and sustainability.

The thermodynamic principles controlling turbine intake pressure and flow rate have a substantial impact on the overall efficiency of a geothermal power plant. The first rule of thermodynamics regulates the relationship between changes in these parameters and the conversion of energy, which directly affects the system's energy production. The second law of thermodynamics emphasizes that changes in pressure and flow rate may lead to a rise in entropy and irreversibilities, resulting in a decrease in both energy efficiency and the quality of energy conversion. In addition to energy efficiency, these interactions have an impact on operational stability, the longevity of components, and power quality. For example, when pressure is not predictable, it may cause mechanical stress and instability, while increasing wear on parts can lead to higher expenses for maintenance and periods of inactivity. In addition, inadequate pressures may reduce thermal efficiency and power quality, which in turn impacts the reliability of energy provided to the grid. Comprehending and controlling these thermodynamic interactions is essential for maximizing the efficiency, dependability, and financial feasibility of geothermal power plants.

This results also suggest that maintaining optimal operating conditions, especially regarding turbine inlet pressure, is crucial for reducing energy losses and improving overall efficiency. Power plant operators can use these insights to fine-tune their systems, ensuring that the turbines are operating under the best possible conditions. This can involve regular monitoring and adjustments to maintain the desired pressure levels. By keeping the inlet pressure at a higher level within the ideal range, the turbine's performance may be greatly enhanced since it allows for more energy to be useful for conversion. Nevertheless, it is crucial to avoid forcing the turbine components to excessive pressures, since this might result in excessive wear and severe harm. Hence, it is essential to achieve an equilibrium that optimizes efficiency while maintaining the long-term reliability of the equipment. Therefore, optimization should be done to observe the tradeoff conflict between the performance and the cost and to see what is the ideal pressure which should be selected.

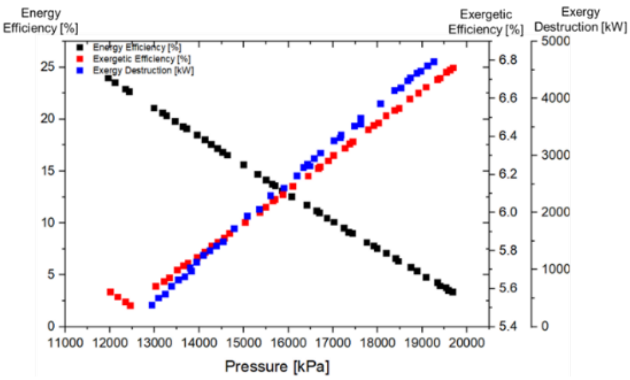

Fig. 2: Comparative graphic between turbine inlet pressure and total exergetic efficiency, energy efficiency and total exergy destruction.

3.3 Parametric Study of Binary Cycle Geothermal Turbine Inlet Temperature

The optimal exit temperature from the evaporator is determined by setting the optimal parameter values of the flow rate of mass of CO_2 rate and pressure at the inlet of the turbine (state 3). As depicted in Fig. 3, energy efficiency increases as the temperature at the inlet of the turbine rises from 120-140°C. When the enthalpy value achieved at the lowest temperature is low, the turbine's work output is correspondingly low. Conversely, as the enthalpy value at the inlet of the turbine grows due to higher temperatures, the turbine's work output also rises. Comparatively, there is an increase in the overall exergetic efficiency when the turbine inlet temperature amplifies, precisely from 5.49% to 6.27%. Moreover, the increase in turbine work surpasses the value of exergy at the turbine intake, improving exergetic efficiency.

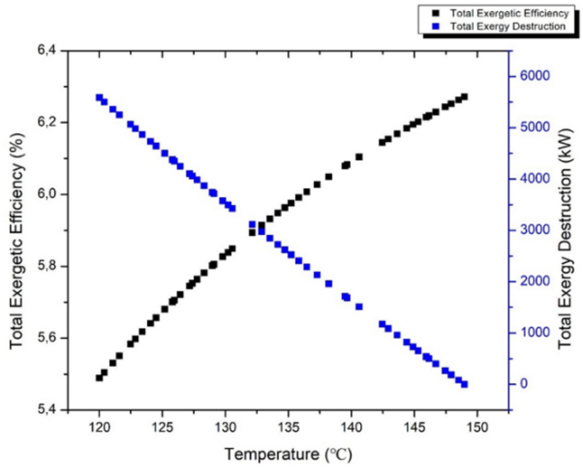

Fig. 3: Comparative graphic between turbine inlet temperature and total exergetic efficiency.

Figure 3 also shows a reduction in the overall exergy destruction value as temperature rises, declining from 5587.09 kW to 0.02 kW. A larger temperature differential from the heat source (turbine inlet) and the heat sink amplifies the potential for extracting useful work. The increase in turbine intake temperature has a parametric effect on the decrease in mass flow rate in the evaporator since it leads to an increase in heat absorption. However, the enthalpy of the turbine intake will likewise rise in direct proportion to the increase in turbine inlet temperature. This component plays a crucial role in enhancing the power output of a CO_2 turbine. Furthermore, there will be a drop in the CO_2 pump because of the reduced mass flow rate in the evaporator, leading to yet another domino effect to increase the thermal efficiency of the system[45]. The turbine's inlet temperature holds significance as it represents the working fluid temperature entering the turbine. A higher inlet temperature enhances the potential for extracting work during expansion. Irreversibilities during expansion, like friction and heat losses, contribute to exergy destruction. Increasing the inlet temperature can help alleviate these irreversibilities by better aligning the working fluid with the turbine design. Higher inlet temperatures not only boost turbine efficiency but also enhance the overall efficiency of the geothermal power plant, converting a larger portion of the extracted heat from the Earth into useful work.

Table 6. Properties and Thermodynamics Analysis of Each Components.

State	Temperature (°C)	mass flow (kg/s)	Pressure (kPa)	Enthalpy (kJ/kg)	Entropy (kJ/kg.K)	Energy (kW)	Exergy (kW)
1 gw	140	100	1500	603.08	2.5096	60308	16515
2 gw	85	100	1500	549.55	2.3706	54955	15307
3 gw	85.07	100	1617.72	548.83	2.3549	54883	15702
1	24.97	112.55	6430	274.65	1.2481	30911.9	23957

State	Temperature (°C)	mass flow (kg/s)	Pressure (kPa)	Enthalpy (kJ/kg)	Entropy (kJ/kg.K)	Energy (kW)	Exergy (kW)
2	45.53	112.55	17780	293.5	1.2602	33033.4	25670
3	130	112.55	17780	500.29	1.8407	56307.6	29466
4	49.88	112.55	6430	462.39	1.8707	52042	24194
1 cw	15	643.49	300	63.27	0.22	40713.6	592
2 cw	22.84	643.49	300	96.07	0.34	61820.1	148

3.4 Parametric Study of Binary Cycle Geothermal Turbine Inlet Mass Flow Rate

To establish the ideal CO_2 cycle mass flow rate value in the 120°C to 140°C, the parametric study was performed by considering the optimal parameters of turbine intake temperature and turbine inlet pressure. When compared to the entire exergetic efficiency value, there was an increase as the mass flow rate increased, precisely from 5.83% to 5.83%. This increase in mass flow rate generates an increment in turbine work and exergy values for each component that receives CO_2. This causes the overall exergy destruction value to drop as the mass flow rate of the CO_2 cycle increases. In Fig. 4, it is proven that with the increased rate flow of mass, the overall exergy destruction value decreases, dropping from 4348.53 kW to 3585.73 kW. This effect occurs as a result of reduced energy loss inside the system. By increasing the mass flow rate of the working fluid, the heat exchanger could absorb heat more efficiently, leading to less energy loss in the heat transfer process and lower exergy destruction. Increasing the mass flow rate in the turbine results in a more uniform temperature and pressure distribution. This leads to improved efficiency in the work output of the turbine by reducing local inefficiencies, such as pressure drops and flow separation, which are known to cause exergy destruction.

Higher mass flow rates contribute to maintaining a smaller differentiation of temperature between the primary fluid and the working fluid, which enhances the efficiency of the heat transfer process. Additionally, it improves the convective transfer of heat between the primary and working fluids, ensuring more efficient heat transfer to the working fluid for power generation. This reduction in heat losses to the surroundings improves overall efficiency. Moreover, increasing the mass flow rate can mitigate irreversibility by reducing the impact of friction and heat transfer losses. Increasing the mass flow rate serves as a strategy to optimize system efficiency and minimize losses, thereby maximizing the effective utilization of available thermal energy.

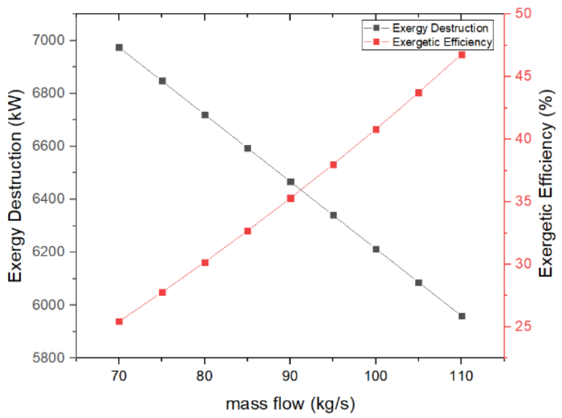

Fig. 4: Comparative graphic between mass flow rate and total exergetic efficiency and total exergy destruction.

Contrary to the expectation, a lower flow rate will indeed result in lower overall efficiency. The power generated by the turbine is directly proportional to the mass flow rate of the working fluid entering the turbine. If the system has a low flow rate, it will lead to a decrease in the energy produced. Additionally, in a binary geothermal plant, which utilizes heat exchangers for heat release and absorption, the lower flow rate will impact the heat transfer efficiency. A reduced flow rate will decrease the effectiveness of heat transfer between the CO_2 working fluid and the geothermal fluid.

Operating at a lower flow rate often requires the turbine to work under non-optimal conditions, resulting in increased frictional losses and other inefficiencies. These additional sources of inefficiency contribute to the destruction of available energy, thus reducing the overall efficiency of the system. Furthermore, the mass flow rate has an impact on the ratios of pressure throughout the turbine. Reducing the flow rate might potentially change the pressure drop, resulting in inefficient expansion of CO_2 in the turbine. This may decrease the conversion efficiency of thermal energy into mechanical energy, so negatively impacting the overall efficiency of the system.

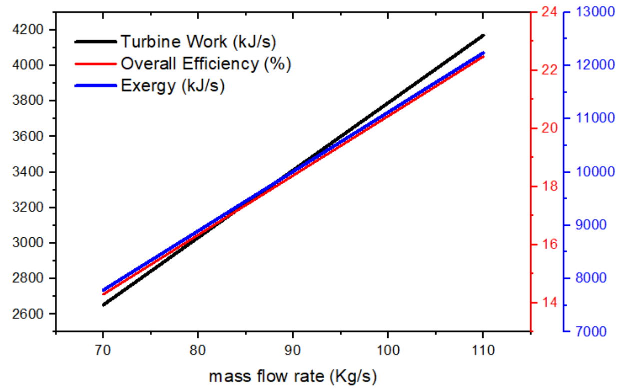

Fig. 5: The relation between Mass Flow Rate, Turbine Work, Overall Efficiency, and Exergy of Turbine.

Figure 5 depicted the relation between mass flow rate with turbine work, overall efficiency, and exergy value of the turbine. As the mass flow rate rises from about 70 kg/s to 110 kg/s, turbine work shows a significant increase from approximately 2600 kJ/s to over 4200 kJ/s. This indicates a direct correlation where a higher mass flow rate leads to greater energy output by the turbine. Further, the efficiency appears to climb steadily from about 14% to nearly 24% as the mass flow rate increases, demonstrating that enhancing the mass flow rate positively impacts the system's efficiency. This suggests that optimizing the mass flow rate is crucial for maximizing the performance and energy efficiency of the system. However, it is essential to consider operational limits and the potential impacts on other system components when increasing the mass flow rate.

3.5 Exergy Destruction Analysis of Each Component

For a comprehensive exergy destruction analysis for each component in a geothermal power plant, it is customary to consider the primary components inherent in such a system. Each component plays a specific role in converting geothermal heat into electricity. The analysis involves identifying sources and magnitudes of exergy destruction in each component using principles of thermodynamics' second law. The results of the exergy destruction are summarized in Figure 6, which illustrates that the high exergy destruction value indicates a significant loss of available energy due to inefficiencies. Strategies to mitigate exergy destruction and enhance the system's overall efficiency include adjusting parameters that are critical, consisting of mass flow rate, temperature, and pressure.

The turbine experiences approximately 2200 kW of exergy destruction, the highest in the system. Figure 6 shows the significant irreversibility and inefficiencies within the turbine, making it the largest contributor to exergy destruction in the system. There are many ways to increase turbine efficiency. Minimizing pressure drops in the turbine and associated piping by optimizing the geometry and smoothing internal surfaces can decrease exergy destruction. Moreover, ensuring that the turbine operates at optimal pressure ratios also can help. Then, using materials with higher temperatures and corrosion resistance can reduce wear and degradation in the turbine, leading to better performance over time and reduced maintenance needs[46]. Incorporating regenerative feed heating cycles, where the geothermal fluid preheats incoming fluid, can also help recover some of the thermal energy that would otherwise be lost, effectively increasing the cycle efficiency[47]. Further, implementing advanced control systems that optimize the operation of the turbine in real-time can help reduce inefficiencies. These systems can adjust parameters dynamically to reduce losses and maintain the turbine's performance at its peak. Finally, regular maintenance to check for mechanical issues, such as misalignment or wear in the turbine blades, and a continuous monitoring system to promptly address inefficiencies are critical for maintaining optimal performance. By implementing these techniques, a geothermal power plant can significantly enhance the efficiency of its turbines, thus reducing exergy destruction and improving overall energy production. As a case study, Alfian Hardi Qurrahman et al. conducted a research study on the geothermal powerplant located at the Dieng Geothermal Power Plant in Indonesia. During the study, it was discovered that the turbine had significant exergy destruction due to the high incoming steam temperature, resulting in an excessive quantity of energy in the turbine. This phenomenon arises due to a discrepancy between the amount of steam injected into the turbine and the capacity of the turbine. Therefore, it is recommended that the steam capacity be decreased to match the turbine's capacity, reducing exergy destruction[48].

The second largest exergy destruction in the system is the evaporator reaching above 1000 kW in the bar chart. This component also shows significant exergy loss, reflecting inefficiencies in heat transfer processes within the evaporator. Two approaches reduce the evaporator's exergy destruction. The first way to improve heat transfer efficiency is to increase the heat exchanger configuration's surface area and add inserts or baffles within the tubes to increase fluid turbulence, disrupting the flow pattern and lowering thermal resistance. Second, by aligning this optimization with the thermodynamic properties of CO_2, pressure and temperature levels may be adjusted. Utilizing real-time data may assist in keeping the evaporator working at its most productive setting. Improving the design and efficiency of the evaporator can minimize temperature differences between interacting fluids, thereby reducing thermal losses and exergy destruction.

The total cost rate equation is used in exergoeconomic analysis to determine how much is spent per unit of time ($/s). To compute the total cost rate value, equation (5) is used to calculate the Capital Recovery Factor (CRF). If the derived CRF value is 0.06, the total cost rate value may be determined using equation (7). Table 7 illustrates the expenses incurred by each state, which are calculated by multiplying the individual expenditures by the exergy rate for each state. State 3 evaporator output has the highest cost expenditure, 3.32 \$/s, while state 2cw CT pump output has the lowest cost expenditure, 0.00008\$/s. The overall expenses for all geothermal binary cycle states are 13.27 \$/s.

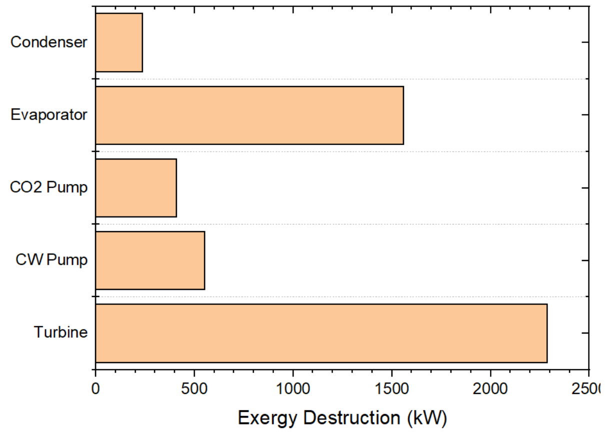

Fig. 6: Exergy Destruction of Each Components.

Table 7. Cost Rate of Each States.

State	**Ċ (\$/s)**
C1gw	0.00276
C2gw	0.00086
C3gw	0.00086
C1	3.31463
C2	3.31525
C3	3.31662
C4	3.31472
C1cw	0.00024
C2cw	0.00008
C3cw	0.00019
Total	13.26620

3.6 Multi Objective Optimization of CO_2 Binary Geothermal Power Plant

The multi-objective optimization of a CO_2 binary geothermal power plant entails simultaneously optimizing several conflicting objectives to identify a set of results that represent a trade-off among these objectives. The primary goals in optimizing a CO_2 binary geothermal power plant commonly involve maximizing energy output, enhancing efficiency and minimizing overall costs. This research focuses on critical component parameters achieved by increasing the mass flow rate and optimizing temperature at inlets of turbine and pressure levels. Parametric studies have been carried out to evaluate how these three variables impact exergetic efficiency, exergy destruction, energy efficiency, and cost rate. As indicated in Fig.7, the higher the energy efficiency value attained, the greater the total cost will be. This suggests that higher investments in the system can lead to better efficiency, likely due to the incorporation of more advanced technologies or optimized operational strategies. However, this increase in cost needs to be justified by the corresponding gains in efficiency to ensure economic feasibility. Decision-makers must consider how much additional cost is acceptable for incremental efficiency improvements.

The MOGA provides multiple optimal or near-optimal solutions, as evidenced by the clustering of data points in the graph. These clusters offer a variety of alternatives for system design and operation, as they represent distinct trade-offs among the three performance metrics. For example, certain clusters may prioritize cost-effectiveness with moderate efficiency and exergy degradation, while others might choose to achieve the maximum possible efficiency despite the resulting increased cost. The set of solutions that offer the best trade-offs, where no single solution is superior in all aspects, is represented by the Pareto front, which is formed by the boundary of these clusters.

We can quantitatively assess the effectiveness of each solution in terms of cost, energy efficiency, and exergy degradation by applying TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) to the data points from the Pareto graph. The solution closest to the ideal solution in terms of relative proximity is the most optimal, as it represents the best compromise among the multiple objectives. The optimum value from this analysis is obtained as in Table 8, where the efficiency of energy, total cost, and destruction of exergy were 30%, 1427 kW, and 0.14 \$/s. This is because obtaining high energy efficiency requires a good dynamic control system for these three parameters, which results in quite high initial costs. Meanwhile, for exergy destruction, the value will decrease as energy efficiency increases. Higher energy efficiency implies a reduction in thermodynamic irreversibility. Minimizing irreversibilities is synonymous with reducing exergy destruction. Achieving greater energy efficiency often involves designing components to match temperatures effectively, which minimizes exergy losses associated with temperature differences.

Towhid Parikhani et al. (2021) provided similar findings to the study results, showing that using CO_2 fluid would generate an energy efficiency of up to 7.64%[49]. Another study by Mohammad H. Ahmadi et al. (2016) found that the exergy efficiency and total cost production of geothermal power plants utilizing CO_2 as the working fluid is 20.5% and 263592.15 \$/year[50]. To achieve the identified optimal solution, specific operating variables need adjustment. These variables include temperature (140°C), pressure (19950 kPa), and mass flow rate (100.95 kg/s). Setting the temperature at 140°C suggests that this particular temperature value contributes to the optimal performance in relation to energy efficiency, exergy destruction, and cost rate. An adapted sliding pressure operation management approach maintains a consistent temperature differential between the heat source temperature and the CO_2 turbine input temperature[51].

Table 8. Result of MOGA Optimization.

Rank	Parameter			Objective Function		
	T (°C)	P (kPa)	m (kg/s)	Total cost ($/s)	Exergy destruction (kW)	Energy efficiency (%)
50	124.85	17728	85.14	0.095	7884	2.93
1	140	19950	100.95	0.14	1427	30

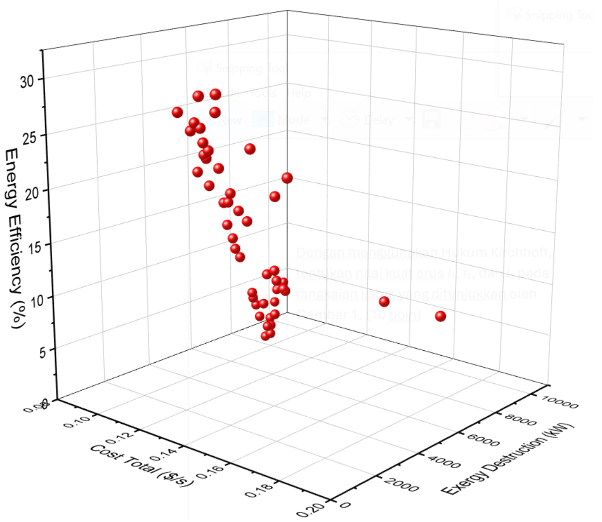

Fig. 7: 3D MOGA Optimization.

The specified pressure setting at 19950 kPa is considered optimal for the desired outcomes, indicating a trade-off that minimizes exergy destruction and cost rates. A mass flow rate of 100.95 kg/s is determined to be optimal. This adjustment likely balances the energy extraction from the geothermal source with the efficiency and cost considerations. The adjustments to operating variables showcase a delicate balance between conflicting criteria, demonstrating how the TOPSIS method aids in making decisions that consider multiple objectives simultaneously. The identified optimal solution is not solely focused on one criterion but considers a holistic set of criteria, aligning with the complexities of geothermal power plant operation. The findings highlight the importance of optimizing key parameters, such as flow rate and turbine inlet pressure, to maximize efficiency. For geothermal power plants, this means that during the operation, engineers should focus on achieving the ideal balance between these parameters to ensure the system operates at peak efficiency.

4. Conclusion

This research optimizes a binary geothermal power plant utilizing CO_2 as the working fluid and explores the integration of Carbon Capture Utilization and Storage (CCUS) with Geological Carbon Storage (GCS) in geothermal energy systems. This study evaluates the impact of temperature, pressure, and mass flow rate on the plant's exergetic efficiency and exergoeconomic performance through comprehensive thermodynamic analysis. The genetic algorithm facilitated the determination of the most favorable operating settings, resulting in 140°C for temperature, 19950 kPa for pressure, and 100.95 kg/s for mass flow rate at the turbine inlet, resulting in a 30% energy efficiency and an exergoeconomic value of 0.14 $/s. The results suggest optimizing the operational parameters to make geothermal power generation more efficient and cost-effective. This finding means utilizing CO_2 as a working fluid in a binary geothermal power plant is a realistic option. The outcomes of this investigation provide significant value to the ongoing efforts to reduce carbon emissions and promote sustainable energy alternatives. Besides that, using CO_2 as the working fluid can effectively reduce greenhouse gas production in the atmosphere, contribute to a cleaner power production system, offer long-term environmental benefits such as cleaner air, and reduce the rate of global warming. Hence, this can be an effort towards a Net Zero Emission program, since this program is the global interest on handling the sustainability challenge. This integration of CO_2 as the working fluid in geothermal power plan also could serve as a complementary technology to traditional water-based systems, particularly in regions facing water scarcity. Though, this study only evaluates the performance of geothermal power plants utilizing CO_2 as the working fluids in thermodynamic calculation, a more advanced study using a simulation program can be done to support the finding of this study. This study also only assesses the exergy efficiency and exergoeconomics from utilizing CO_2 in the binary geothermal power plants, and the simulation tool can be use in evaluating the efficiency of the other type of geothermal power plant, with the finding from this study being the basis. This research enhances the existing understanding of geothermal energy by presenting a well-defined framework for maximizing the efficiency of binary systems that employ CO_2. Essentially, this study not only determines the best conditions for running a geothermal power plant using CO_2 but also shows how these discoveries might improve the efficiency and economic feasibility of sustainable energy systems. This finding signifies a significant advancement in pursuing more efficient and enduring geothermal energy generation.

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Nomenclature

EOR	Enhanced Oil Recovery (-)
CCUS	Carbon Capture and Utilization or Storage (-)
$O\&M$	Operational and Maintenance (-)
CRF	Capital Recovery Factor (-)
CPG	CO_2 Plume Geothermal (-)
sCO_2	Supercritical CO_2 (-)
GA	Genetic Algorithm (-)
S_{gen}	Entropy generation (kJ K^{-1})
W	Work (kJ)
$\dot{W}$	Work Rate (kW)
E	Exergy (J)
T	Temperature (K)
T_0	Environment Temperature (K)
Q	Heat (kJ)
η_{Ex}	Exergetic Efficiency (-)
P_o	Environment Pressure (Pa)
V	Volume (m^3)
X	Quality (-)
$\dot{Z}$	Investment Cost rate (\$ s^{-1})
$\dot{m}$	Mass Flow Rate (kg s^{-1})
$\dot{E}$	Exergy rate (W)
$\dot{C}$	Cost rate (\$ s^{-1})
c	Specific cost (\$ kg^{-1})
h	Enthalpy (J)
s	Entropy (J K^{-1})
g	Gravity (m s^{-2})
cw	Cooling water (-)
gw	Geothermal water (-)
i	Inlet
n	number of periods
o	Outlet

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