Assessment and optimization of a single flash geothermal system recovered by a trans-critical CO_2 cycle using different scenarios

Yashar Aryanfar[1], Siamak Hoseinzadeh[2], Mario Lamagna[2], Benedetto Nastasi[2], Davide Astiaso Garsia[2], Soheil Mohtaram[3], HongGuang Sun[1*]

[1] State Key Laboratory of Hydrology-Water Recourses and Hydraulic Engineering, International Center for Simulation Software in Engineering and Sciences, College of Mechanics and Materials, Hohai University, Nanjing 210098, Jiangsu, China

[2] Department of Planning, Design, and Technology of Architecture Sapienza University of Rome, Rome 00196, Italy

[3] School of Energy and Power Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China

Abstract: Globally, the use of renewable energy, particularly geothermal energy, is rising quickly. Geothermal cycles' low efficiency has repeatedly shown how crucial it is to recover heat lost during these cycles. This study suggests a combined power generation cycle replicating using the EES software environment that combines a single flash cycle with a trans-critical carbon dioxide cycle. The findings demonstrate that, in comparison to the BASIC single flash cycle, the design characteristics of the proposed system are greatly improved. The suggested strategy is then enhanced by employing the genetic algorithm, the Nelder-Mead Simplex method, and the direct algorithm. Separator pressure, steam turbine outlet pressure, and carbon dioxide turbine inlet pressure are three assumed variable parameters, and exergy efficiency is the target parameter. In the default operating mode, the system exergy efficiency is 32.46%, increasing to 39.21% using the genetic algorithm and 36.16% using the Nelder-Mead method and 38.82% using the direct algorithm.

Keywords: Optimization, Single flash Geothermal, Genetic Algorithm, Nelder-Mead Simplex, Direct Algorithm, trans-critical CO_2 cycle

1. INTRODUCTION

The planet's population is increasing yearly, and energy needs are increasing daily. The most important source of human energy in the world is fossil fuels. However, fossil fuel sources are not renewable and bring important environmental risks [1]. In recent years, the environmental effects caused by fossil fuels have become more visible. Global warming has led to the melting of the polar ice caps and endangered all creatures' lives. Also, natural fires and storms have caused irreparable dangers. For this reason, alternative and clean energy sources for fossil fuels have received much attention in recent years. Solar, wind, water, fuel cell, geothermal and biomass energies are among the renewable energies [2]. Choosing a clean energy production method depends on various factors, including geographical and biological conditions and operating costs. In addition, energy conversion processes must be free of environmental hazards, and their adverse effects, such as the production of extreme heat and the release of environmental pollutants, must be avoided. Choosing a clean energy production method depends on various factors, including geographical and biological conditions and operating costs [3]. In addition, energy conversion processes must be free of environmental hazards, and their adverse effects, such as the production of extreme heat and the release of environmental pollutants, must be avoided. Among the clean energy production methods, the use of wind and water energy has the lowest cost, and the use of solar energy has the highest cost. Due to some advantages, geothermal energy is one of the suitable options for renewable energy production. Unlike other renewable energies, geothermal energy is not limited to specific seasons, times and conditions and can be used without interruption. Also, the cost of electricity in geothermal power plants is competitive with other common (fossil) power plants and is even cheaper than other new energy types. Therefore, geothermal resources are of particular importance due to their availability, simple technology for creating power plants, the possibility of uninterrupted operation and long-term use [4].

The heat extraction capabilities of the N_2O, CO_2, and H_2O EGS[1] were analyzed and compared by Liu et al. [5]. A two-dimensional thermo-hydraulic-mechanical (THM) coupled EGS model with discrete fractures is established. The effects of the injection-production parameters on the heat extraction outcomes of the EGS with various working fluids are also examined. According to the findings, N_2O-EGS and CO_2-EGS perform nearly identically in heat extraction under the same circumstances. Sahana et al. [6] investigated a supercritical CO_2 power cycle proposed to recover the heat of the hot water obtained at a temperature close to 140 °C from the oilfield in the HWCS. An ejector expansion CO_2 refrigeration cycle uses the output power of the supercritical CO_2 power cycle to run its compressor. The HDH (Humidification-dehumidification) desalination unit partially uses the rejected heat of CO_2 cycles. A coupled thermal model for this system is proposed by Liao et al., considering the coupling effects of temperature and pressure on CO_2 flow and heat transfer. According to the simulation results, at 230 m of well separation, the thermal breakthrough time is roughly 40 days. Wang et al. [7] ran simulations of geothermal heat mining using supercritical CO_2 (sCO_2) in this study. Subcritical, superheated, and supercritical organic Rankine cycles (ORCs) working fluid selection criteria are then provided for power generation using sCO_2 from a geothermal reservoir. A working fluid classification method for ORC is being proposed in the meantime. Jiang et al. [8] used models to forecast the system efficiencies for the two standalone and hybrid systems. Compared to standalone CO_2-EGS and CO_2-solar thermal systems, it has been discovered that the hybrid system has an efficiency that is on par with or even higher than the combined efficiency of the two individual systems.

This research calculates a power generation system's energy and exergy efficiency using a combined single flash geothermal source with a trans-critical carbon dioxide cycle. Essential performance parameters, including separator pressure, the inlet pressure of the carbon dioxide

1 Enhanced Geothermal System

turbine and the steam turbine outlet pressure, will be examined to determine the optimum operating point. The novelty of the present work is the optimization of the main parameters of the recovery system to achieve the maximum possible efficiency by simultaneously using the genetic algorithm and Nelder-Mead simplex method. The main aims of this research are:

- Modeling a single flash geothermal power plant powered by a transcritical CO_2 Cycle
- Optimize the system based on the GA[2] and NMS[3] and DA[4] methods, find the best system performance and maximize efficiencies.
- Comparison of optimization results of the algorithms and method used to identify more effective optimization tools.
- Studying changes in energy efficiency, exergy, and total output power relative to the basic parameters of the system.

2. Proposed system description

Figures 1(a) and 2(a) depict the basic single-flash geothermal cycle and single-flash geothermal cycle powered by the trans-critical carbon dioxide cycle that has been suggested. Also, Figure 1(b) shows the temperature-entropy diagram of the single flash geothermal basic cycle. Also, Figure 2(b) presents the temperature-entropy diagrams of the single flash section, and Figure 2(c) presents the temperature-entropy diagram of the trans-critical carbon dioxide section in the proposed recovery system. Software called Engineering Equation Solver (EES) was used to simulate the system. In the simulation technique, each system component is used as a control volume engineering, and the first and second laws of thermodynamics are applied to it.

As shown in Figure 2(a), some geothermal fluid that has entered the system is transformed into two-phase fluid during the decompression process, in which the pressure drop occurs at a

[2] Genetic Algorithm
[3] Nelder-Mead Simplex
4 Direct Algorithm

constant enthalpy. The two-phase fluid then enters the separator, where the saturated vapor part of the fluid generates energy in the steam turbine. Before the heat exchanger's outlet fluid is returned to the ground, the saturated liquid section of the separator also enters the vapor generator (VG), which elevates the temperature of carbon dioxide gas. It enters the gas turbine at the right temperature and pressure, producing more power for the entire system. This research differs from past investigations because it incorporates a heat exchanger into the carbon dioxide cycle. The system's performance is enhanced by this heat exchanger, which warms the incoming gas to the vapor generator using the heat of the output fluid from the single-cycle steam turbine. The output fluid of the steam turbine is sent to the re-injection well after going through the heat exchanger and cooling in a condenser.

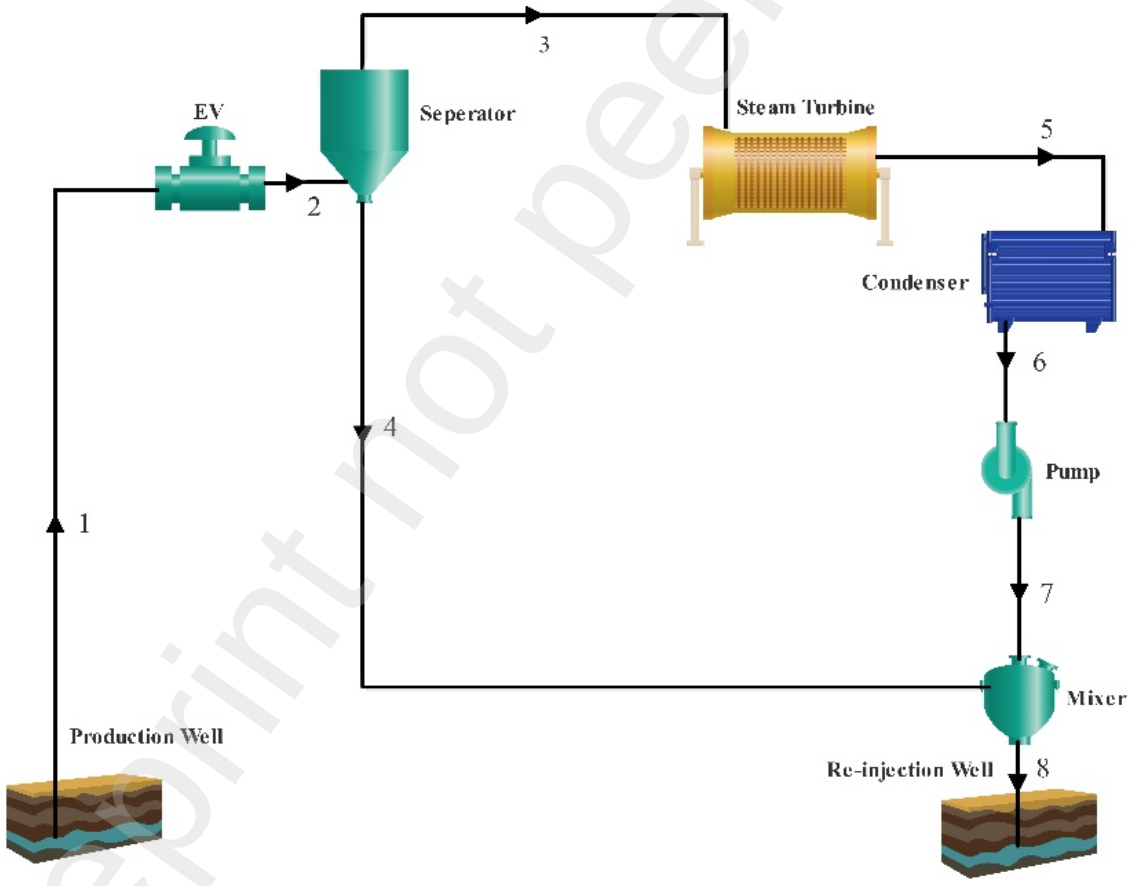


Figure 1(a). Schematic of basic single flash geothermal power plant.

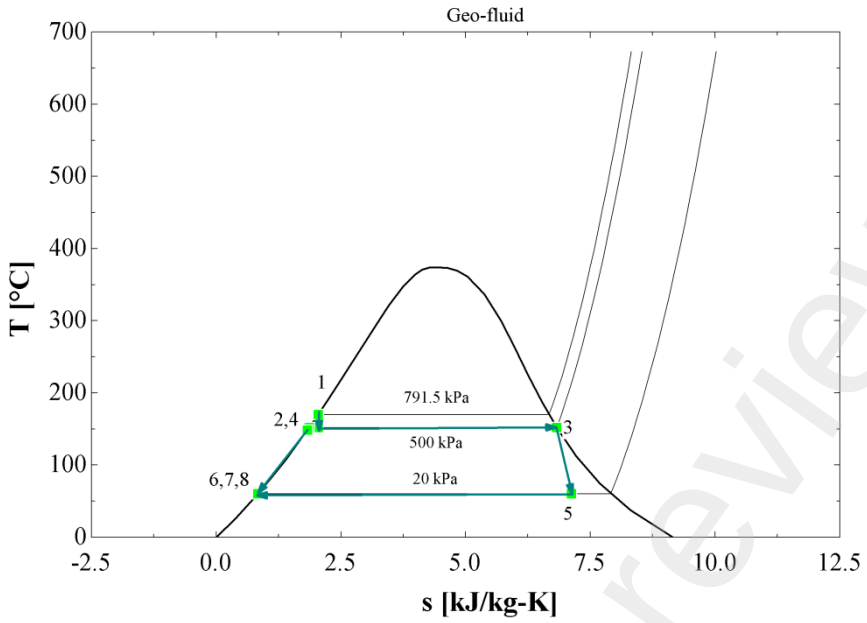


Figure 1(b). Single flash geothermal power plant T-S diagram.

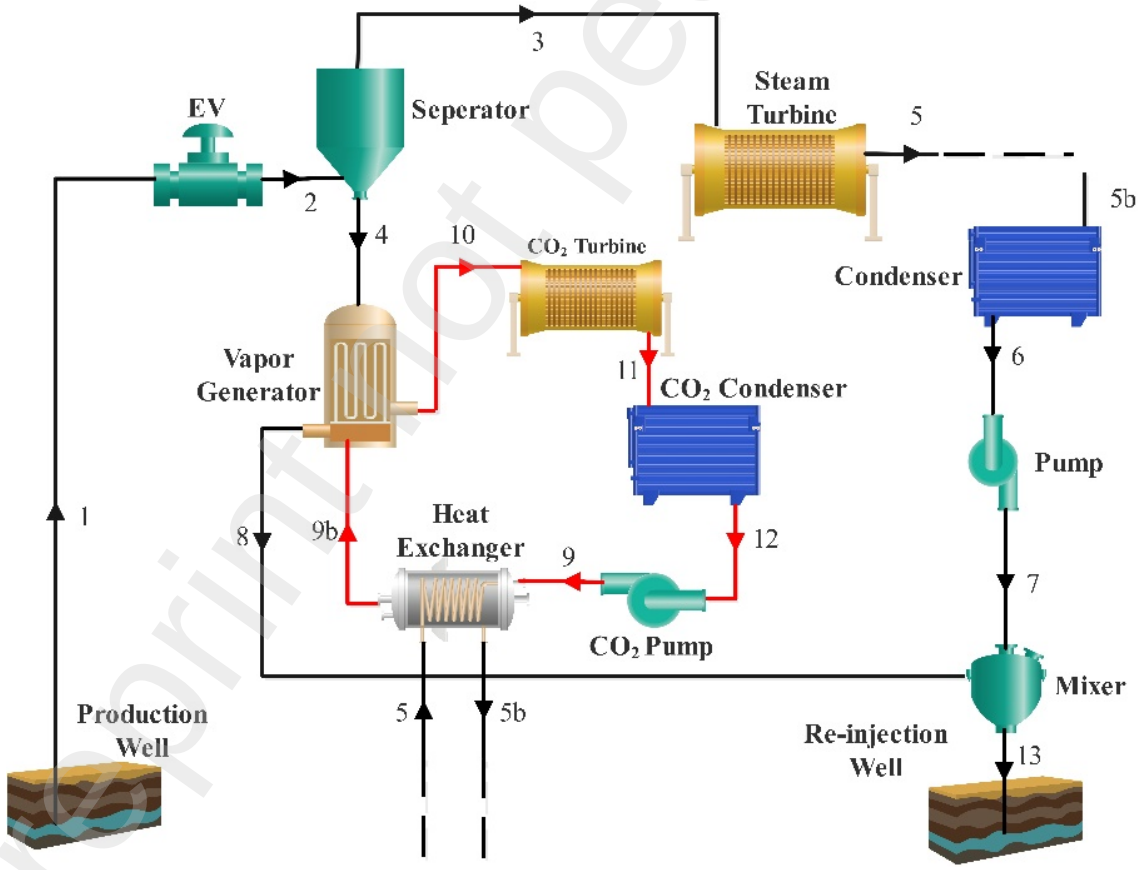


Figure 2(a). Schematic of single flash geothermal power plant powered by a trans-critical CO_2 cycle.

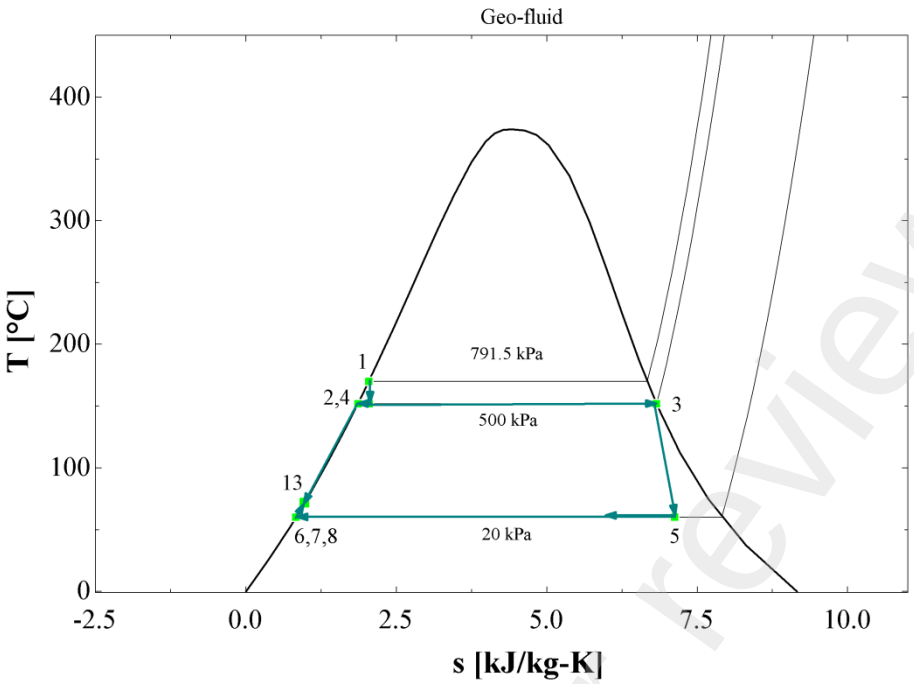


Figure 2(b). Single flash geothermal power plant T-S diagram in the recovery mode.

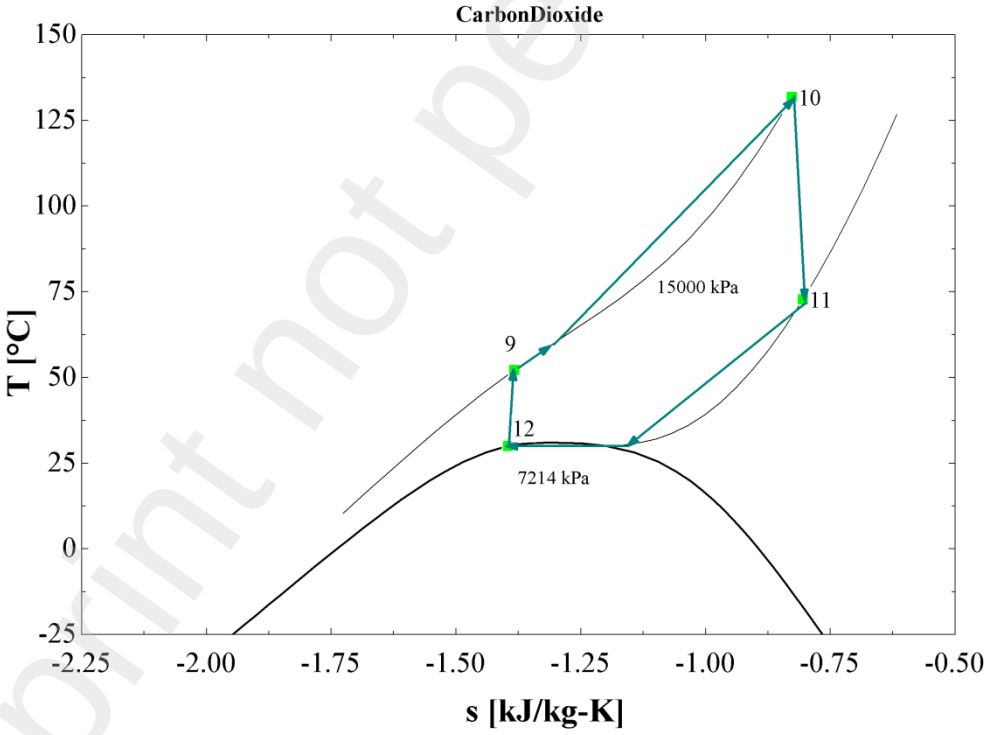


Figure 2(c). T-S diagram of trans-critical CO_2 cycle in the recovery mode.

Finding the congestion point in a trans-critical cycle is challenging since the temperature change's slope fluctuates as carbon dioxide gas warms up inside heat exchangers like an

evaporator. The temperature difference between the beginning and end is treated as constant for ease of solution.

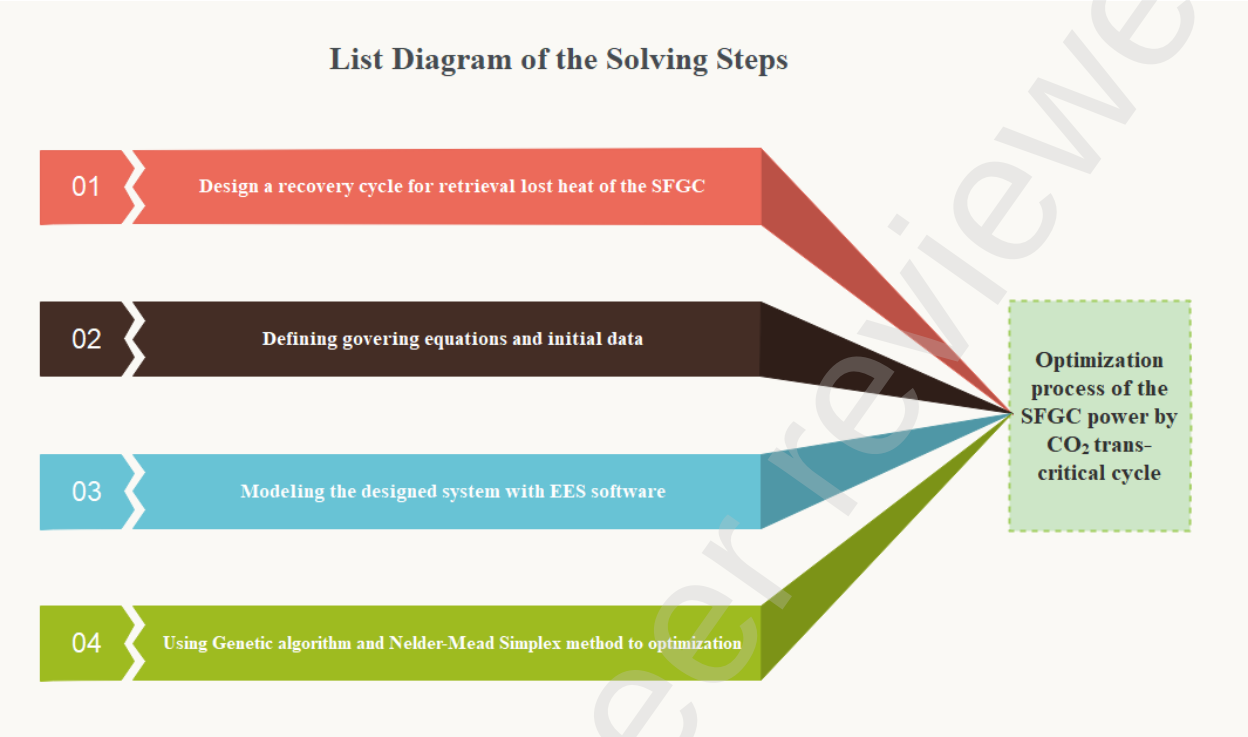


Figure 3. List Diagram of the problem solution process

Figure 3 shows the list diagram of the research steps. According to Figure 3, in the present work, in the first step, the primary single flash geothermal cycle and recovery trans-critical CO_2 cycle are designed to recover dissipated heat. In the second step, the initial data, and governing equations of the systems under study are defined using the research literature. The proposed recovery system is simulated in the EES software environment in the third step. In the last step, the results are optimized using genetic algorithms, the Nelder-Mead Simplex method, and the direct algorithm.

3. Governing Equations

According to equations (1) and (2) and neglecting kinetic and potential energies, the system is written while considering the control volume, mass, and energy balances for each component of the system (2) [9-13]:

$$\sum \dot{m}_i = \sum \dot{m}_o \quad (1)$$

$$\sum \dot{Q} + \sum \dot{m}_i h_i = \sum \dot{m}_o h_o + \dot{W} \quad (2)$$

Equations (3) and (4) will yield the isentropic efficiency and net power production of each turbine:

$$\eta_{Tur} = \frac{h_i - h_o}{h_i - h_{o,s}} \quad (3)$$

$$\dot{W}_{Tur} = \dot{m}_i (h_i - h_o) \quad (4)$$

The isentropic efficiency and net power of each pump are represented as follows:

$$\eta_{Pump} = \frac{h_i - h_{o,s}}{h_i - h_o} \quad (5)$$

$$\dot{W}_{Pump} = \dot{m}_i (h_o - h_i) \quad (6)$$

Equations (7), (8), and (9) will represent the net power of the system as well as the energy efficiency and exergy efficiency of the entire system [14-16]:

$$\dot{W}_{net} = \dot{W}_{tur,steam} + \dot{W}_{tur,CO2} - \dot{W}_{pump,steam} - \dot{W}_{pump,CO2} \quad (7)$$

$$\eta_{en} = \dot{W}_{net} / \dot{Q}_{in} \quad (8)$$

$$\eta_{ex} = \dot{W}_{net} / E_{in} \quad (9)$$

In the current investigation, the following hypotheses are considered [17-19]:

1. All cycle parts function in steady-state situations (as a control volume).
2. Changes in kinetic energy and potential in all components are insignificant, and pressure drop and heat loss in pipelines can be disregarded.
3. The isotropic efficiency of pumps is 0.75, while that of turbines is 0.8.
4. The ambient temperature and pressure for the analysis that is being presented are 25 °C and 0.1 MPa, respectively.

Table 1. Initial data for modelling [14]

Definition	Values

Ambient temperature (T_0)	25 °C
Ambient Pressure (P_0)	100 kPa
Geothermal fluid inlet temperature (T_1)	170 °C
Geo-fluid mass flow rate ($\dot{m}_1$)	10 kg/s
Geo-fluid inlet pressure (P_1)	Saturated
Separator pressure (P_2)	500 kPa
Steam turbine output pressure (P_5)	20 kPa
CO_2 turbine inlet pressure (P_{10})	15000 kPa
CO_2 condenser temperature (T_{cond})	30 °C
Turbine isentropic efficiency (η_{tur})	0.8
Pump isentropic efficiency (η_{pump})	0.75
Evaporator inlet-outlet difference temperature (ΔT_{TTD})	20 °C
Heat Exchanger Pinch Point (ΔT_{PP})	5 °C

In this section, the suggested system's performance is assessed and analyzed, and the tables reflect the findings of energy optimization and exergy. The input parameter values are listed in Table 1 to examine the impact of various parameters on the system performance. The separator pressure and the difference between the evaporator tightening point temperature and the evaporator temperature determine the net output power, thermal efficiency, and exergy efficiency for the cycles under study. For optimization, we will have equations (10) to (13):

$$F = \eta_{ex}(P_2, P_5, P_{10}) \tag{10}$$

$$200 < P_2(kPa) < 800 \tag{11}$$

$$12000 < P_{10}(kPa) < 18000 \tag{12}$$

$$10 < P_5(kPa) < 40 \tag{13}$$

4. Results and discussions

The genetic algorithm (GA) is a popular metaheuristic technique for optimizing stated functions in a confined area. According to the algorithm's inheritance, past information is retrieved and employed in the search process. In 1989, Goldberg invented the principles of the genetic algorithm. An Evolutionary Guideline is the simulation approach described below. The Evolutionary Guideline simulation technique is a neighborhood search strategy that works the same way as a gene does [20].

Furthermore, The Nelder–Mead Simplex method, first published in, is a commonly used DS optimization approach that has been used for various unconstrained problems. NMS uses an iterative technique to generate a series of simplexes that converge to the best answer. When solving an n-dimensional optimization issue, the NMS approach requires n+1 vertices to define the beginning location of the simplex. To alter them simplex shape, you must do the following operations in a single iteration: reflection, expansion, contraction, and reduction. This evolution may continue in an unanticipated fashion, for example, with fewer iterations for a higher number of choice variables, depending on the original simplex's starting position, shape, and orientation [21].

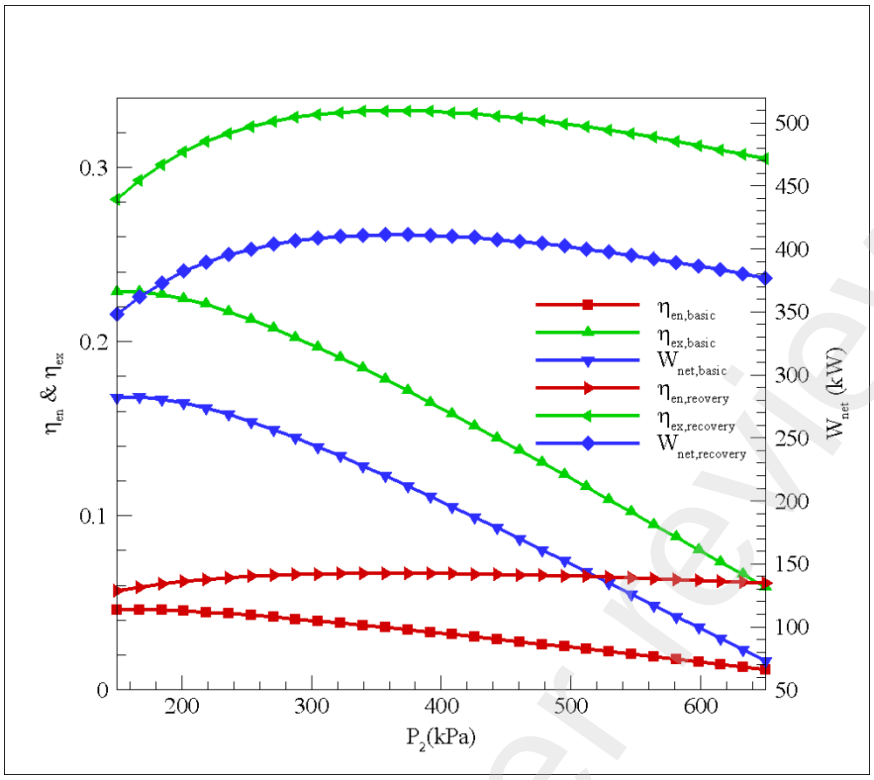
Table 2. Optimum parameters using different scenarios.

Parameters	Initial Mode	Optimal Mode using Genetic algorithm	Optimal mode using Nelder-Mead Simplex	Optimal Mode using Direct algorithm	Unit
Separator pressure	500	304.3	326.4	337.6	kPa
Carbon dioxide turbine inlet pressure	15000	13083	12067	12223	kPa

Steam Turbine exit pressure	20	37.36	22.01	30	kPa
Power production of steam turbine	150.1	194.2	218.1	200.6	kW
Power Production of carbon dioxide turbine	525.5	606.8	460.8	534.4	kW
Electric power consumption of pump 1	0.2436	0.2626	0.2762	0.2732	kW
Electric power consumption of pump 2	274.1	235.6	219	254.9	kW
Net power production	401.3	316	459.5	479.8	kW
Exergy efficiency	32.46	39.21	36.16	38.82	%

The total output of the output is 401.3 kW in BASIC mode, which after adding the recovery cycle, this value reaches 316 kW in the optimized state with the genetic algorithm and 459.5 kW in the optimized form with the Nelder-Mead simplex method and 479.8 kW in the optimized form with the Direct algorithm. Therefore, if the goal is to increase the net output work, the working conditions obtained by the Direct algorithm have a better result.

According to Figure 4, the energy efficiency of the recovery power plant increases monotonically as the separator pressure rises. In contrast, the trend for the energy efficiency of the standalone geothermal power plant is downward because growing separator pressure raises the geofluid-specific enthalpy of the production well. The effect of CO_2 condenser outlet temperature on generated power, energy, and exergy efficiency is depicted in Figure 5. It shows that a significant decrease in net power production is caused by raising the condenser outlet temperature, yet none of these two efficiency losses is substantial. Given that the gas turbine would provide less power, this is a logical outcome.



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189 Figure 4. Energy and exergy efficiencies and net power output variation with separator

190 pressure for basic mode and recovery mode.

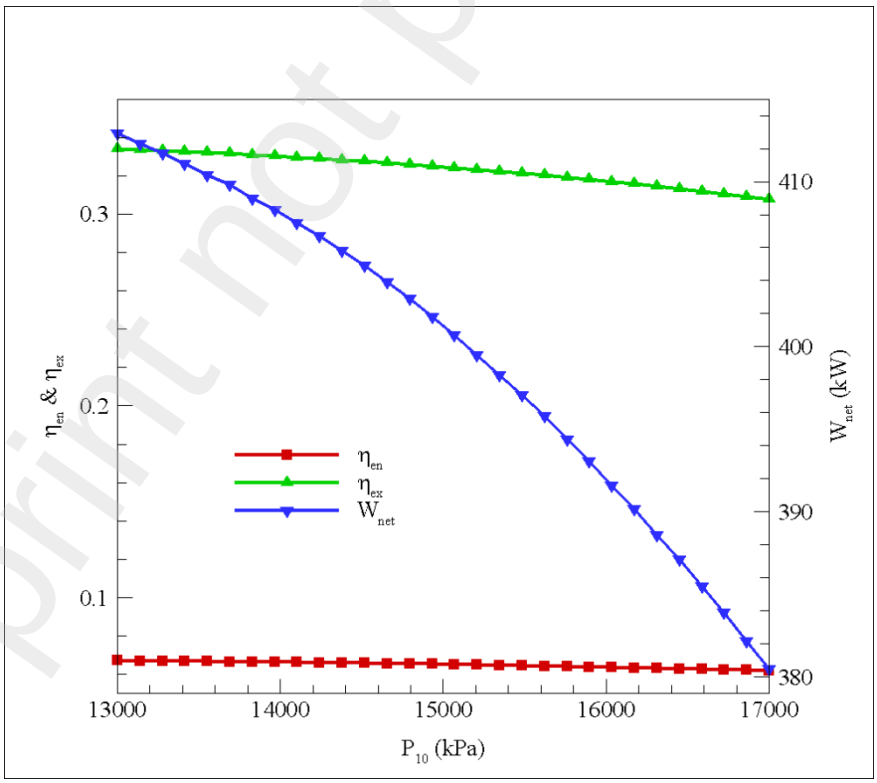

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Figure 5. Energy and exergy efficiencies and net power output variation with CO_2 turbine inlet pressure for recovery mode.

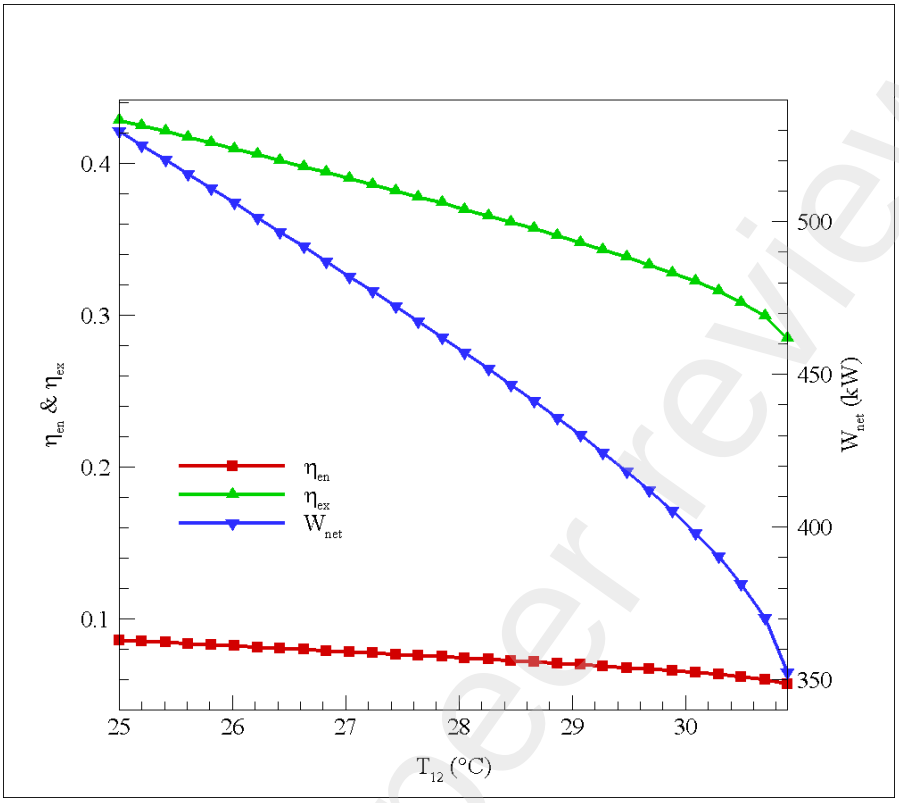

Figure 6. Energy and exergy efficiencies and net power output variation with CO_2 condenser exit temperature for recovery mode.

Figure 6 depicts how a hybrid power plant's CO2 turbine inlet pressure changes the net output energy and accelerator efficiency. The findings indicate that the maximum values of the net power output, exergy, and energy efficiencies occur at about 15 MPa. This can be explained by the fact that raising the gas turbine's inlet pressure raises the inlet temperature of the gas turbine, which increases the condenser's temperature (turbine outlet gas). As a result, the ideal gas turbine inlet temperature is attained, enabling the hybrid power plant to run at its best efficiency.

5. Conclusion

In this research, a combined power generation system (combined single-flash geothermal system with trans-critical carbon dioxide cycle) in energy and exergy in both optimal and primary states have been investigated and researched. Exergy efficiency in the initial state was equal to 32.46%, and after the genetic Algorithm, this value increased to 39.21%. In the case of the Nelder-Mead Simplex method, the exergy efficiency has increased from 32.46% to 36.16%. In the case of the Direct Algorithm, the exergy efficiency has increased from 32.46% to 38.82%. The efficiency of using a genetic algorithm is more effective than other methods.

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