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Exergy analyses and optimization of a single flash geothermal power plant combined with a trans-critical CO_2 cycle using genetic algorithm and Nelder–Mead simplex method

Jian Huang[1*], Azher M. Abed[2*], Sayed M. Eldin[3], Yashar Aryanfar[4*] and Jorge Luis García Alcaraz[5]

*Correspondence:
huangjian108@tom.com;
azhermuhson@uomus.edu.iq;
yashar.aryanfar@gmail.com

[1] Xijing University, Xi'an 710123, Shaanxi, China
[2] Air Conditioning and Refrigeration Technologies Engineering Department, Al-Mustaqbal University College, Babylon 51001, Iraq
[3] Faculty of Engineering, Center of Research, Future University in Egypt, New Cairo 11835, Egypt
[4] Department of Electric Engineering and Computation, Autonomous University of Ciudad Juárez, Av. Del Charro 450 Norte, Col. Partido Romero, Juárez, Chihuahua, Mexico
[5] Department of Industrial Engineering and Manufacturing, Autonomous University of Ciudad Juárez, Av. Del Charro 450 Norte, Col. Partido Romero, Juárez, Chihuahua, Mexico

Abstract

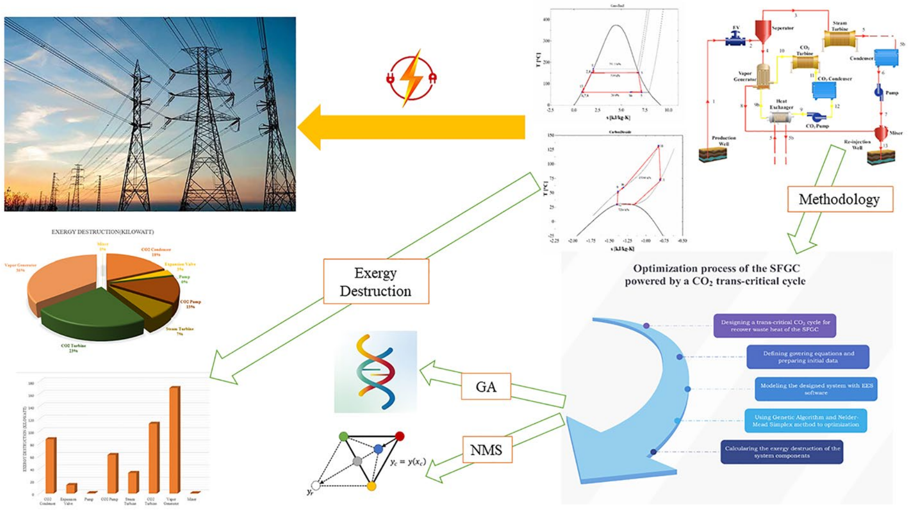
Compared with conventional fossil fuel sources, geothermal energy has several advantages. The produced geothermal energy is safe for the environment and suitable for meeting heating power needs. Because the hot water used in the geothermal process can be recycled and used to generate more steam, this energy is sustainable. Furthermore, the climate change does not affect geothermal power installations. This study suggests a combined power generation cycle replicating using the EES software 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 proposed strategy is then improved using the Nelder–Mead simplex method and Genetic Algorithm. The target parameter is exergy efficiency, and the three assumed variable parameters are separator pressure, steam turbine outlet pressure, and carbon dioxide turbine inlet pressure. The system's exergy efficiency was 32.46% in the default operating mode, rising to 39.21% with the Genetic Algorithm and 36.16% with the Nelder–Mead simplex method. In the final step, the exergy destruction of different system components is calculated and analyzed.

Highlights

- Designing and simulating a combined single flash geothermal cycle with a trans-critical carbon dioxide cycle in the EES software.
- Genetic algorithms (GA) and the Nelder–Mead simplex (NMS) method are used to optimize the proposed system to increase the system's exergy efficiency.
- Examining the system's various components' energy destruction rates.

Keywords: Optimization, Geothermal, Genetic algorithm, Nelder–Mead simplex method, Exergy efficiency, Exergy destruction

Graphical Abstract



Introduction and literature review

The increase in the world's population and the accompanying increase in social welfare are among the most important reasons that have led to the increasing use of all kinds of energy sources, especially fossil sources such as oil, gas, and coal. These fossil resources are becoming more limited day by day and are surrounded by the issue of pollution caused by their use (Islam et al. 2013).

Owing to the negative effects fossil fuels have on the environment, renewable energy sources have recently attracted a lot of attention. Owing to its dependability, stability, and great capacity, geothermal energy has attracted more attention than other renewable sources of electricity (Aneke et al. 2011; Fan et al. 2021; Mohtaram et al. 2021a, b). Despite the high potential of geothermal energy worldwide, however, only a limited part of this resource has been exploited (Li et al. 2021; Pambudi et al. 2021). However, geothermal power plants have become more prevalent recently, and in certain countries, they now account for more than 10% of all electricity output (Chamorro et al. 2012; Pishkariahmadabad et al. 2021).

Numerous studies have been done recently on the analysis and improvement of geothermal power plant cycles (Budiardjo et al. 2021; Pambudi et al. 2018; Rudiyanto et al. 2021). Elbarbary et al. (2022) created the first regional-scale geothermal potential map of Africa using GIS as a tool from various sources. By combining geological thematic levels, geophysical layers, and geothermal layers within the GIS database, they calculated the geothermally attractive places within Africa. With no geo-fluid production to the surface, Akhmadullin and Tyagi (2017) introduced a novel zero mass extraction technique using downhole heat exchangers (DHE). The production and injection components of the well remain connected and continue to be designed as a single horizontal well. At 7000 m well depth, the available power output increases to 600 kW with a competitive energy cost of $21.84/MWh as reservoir temperature and the number of laterals increase.

One of the suggested methods for improving the performance of geothermal systems is the use of combined cycles and the recovery of thermal energy emitted into the environment (Békési et al. 2022). One of the most widely used methods is the organic Rankine cycle. Toxic, flammable, explosive, and expensive are just a few of the downsides that most organic working fluids, including water ammonia, have. Therefore, it is crucial to locate a fluid that works better. CO_2 is easily produced from the environment, has no harmful impacts on the ecosystem, and is non-toxic, non-flammable, and non-explosive. It has been proposed to be utilized as a fluid to generate power. Owing to its low critical temperature, CO_2 can rapidly reach the supercritical state. Using carbon dioxide in the compression cycle reduces system dimensions since it has a low critical temperature, which is its most significant characteristic. As a result of the trans-critical compression cycle of carbon dioxide operating at high pressures, the materials employed in the components are stronger, which is counterbalanced by a reduction in component size and results in a considerable amount of heat dissipation in the gas cooling unit.

In comparison to other refrigerants, it has high latent heat, high thermal conductivity, high thermal resistance, and low viscosity (El Haj Assad et al. 2021a). Ezekiel et al. (2020) in a study with the two objectives of increasing gas recovery (EGR) and obtaining geothermal energy from deep natural gas reservoirs for electricity generation, the potential of extracting heat from produced natural gas and using supercritical carbon dioxide (CO_2) investigated as an active fluid. Sun et al. (2018) developed a model to explain the CO_2 heat and mass transfer mechanism in abandoned horizontal wellbores. With a numerical approach in space, the model was solved. A mechanism for producing geothermal energy was proposed by Wang et al. (2022) (combined single flash geothermal cycle with trans-critical carbon dioxide recovery cycle). A recuperator was employed to recover part of the heat loss to enhance system performance. EES software was used to simulate the suggested system, and the results of earlier studies were used to validate it. The proposed system was examined from an energy and exertion point of view. In a publication, El Haj Assad et al. (2021b) suggested using a single flash geothermal power plant to run a trans-critical CO_2 power plant. The planned combined power plant's energy and exergy analysis has been completed, and the appropriate operating mode for the power plant has been reviewed. The effects of variables such as separator pressure, CO_2 condenser temperature, CO_2 turbine inlet pressure, and the pinch point were identified and discussed on the energy efficiency, exergy efficiency, and output power.

In this study, a single flash geothermal source and a trans-critical carbon dioxide cycle were integrated to calculate a power generation system's energy efficiency and exergy efficiency. The best operating point will be determined by significant performance metrics such as separator pressure, carbon dioxide turbine inlet pressure, and steam turbine output pressure. This work's uniqueness is in presenting a combined geothermal single flash system whose waste heat is recovered using a trans-critical carbon dioxide cycle. An auxiliary heat exchanger is also included in the trans-critical carbon dioxide cycle to increase the system's energy effectiveness. The exergy efficiency of the entire system has been optimized using the genetic Algorithm and the Nelder–Mead simplex method to see how well these two methods perform during the optimization phase. The quantity of energy lost by various system components is computed and shown in the following: a pie chart and a column chart. The principal objectives of this study are:

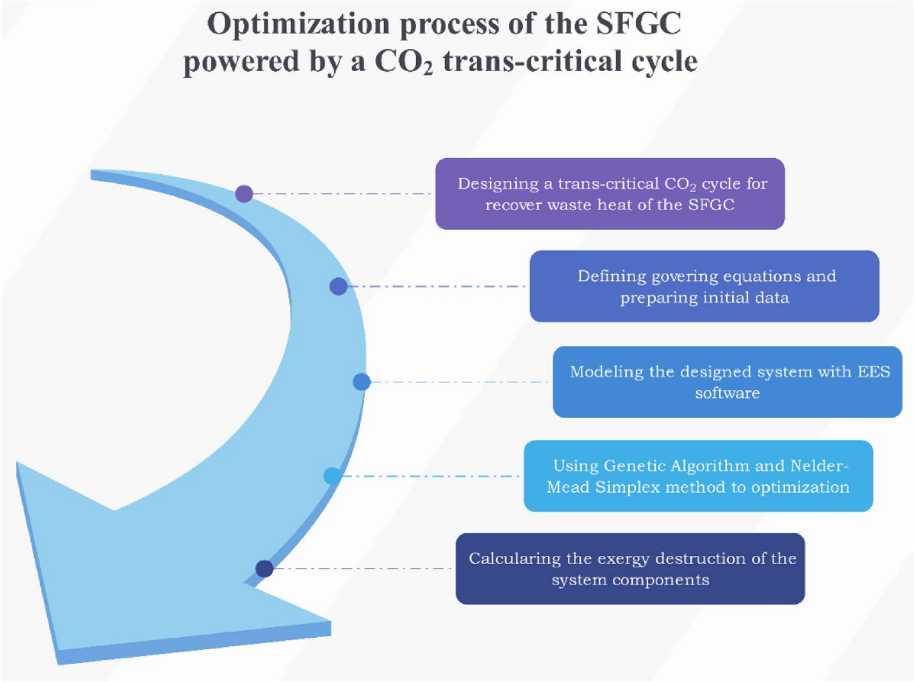


Fig. 1 List diagram of the problem-solving process

- Designing and modeling of a combined single flash geothermal system with a trans-critical carbon dioxide cycle in the EES[1] software environment.
- Optimizing the proposed system using the Genetic Algorithm (GA) and Nelder–Mead simplex (NMS) method to maximize the exergy efficiency of the system.
- Investigating the amount of exergy destruction of different components of the system.

In this work, firstly, the desired system, including a single flash geothermal cycle with trans-critical carbon dioxide recovery, is designed and, using thermodynamic equations and application of initial conditions, in the EES software environment in two functional modes is modeled. Next, using the Genetic Algorithm and the Nelder–Mead simplex method, the designed system is optimized to maximize the exergy efficiency of the total system, and the results are compared with each other. Finally, the exergy destruction of different cycle components is calculated, presented, and discussed in the form of several different diagrams.

Methodology

Figure 1 illustrates how the fundamental single flash geothermal cycle and recovery trans-critical CO_2 cycle are used in the current work's first stage to recover lost heat. In the second step, the research literature defines the beginning data and governing equations of the systems under study. The third stage simulates the proposed recovery

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[1] Engineering Equation Solver.

system in the EES software environment. The genetic algorithm and the Nelder–Mead simplex method are used to optimize the results in the final step. In the following, the exergy destruction of different system components is calculated.

The best member of a collection of feasible members is chosen using mathematical optimization, also known as mathematical programming, in mathematics, economics, and management. In its most basic form, it attempted to determine its maximum and lowest value by methodically choosing data from a readily available set and determining the value of a real function. There are two premises in the field of management:

- No restrictions on resources.
- Existence of limitations in resources.

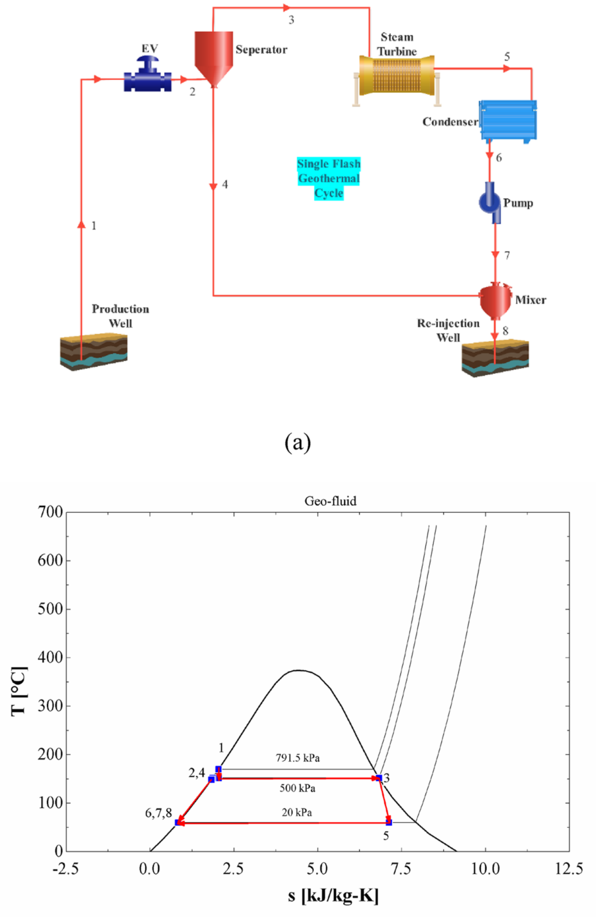
If we accept the first assumption, the optimal value can be estimated from methods, such as taking the first and second derivatives, and if the second assumption is accepted, depending on the organizational and economic problems, we can use models such as linear model, integer model, ideal model, non-linear model, coefficient Lagrange designed, deterministic or probabilistic, etc. and moved towards the optimal point by using existing methods (Pan et al. 2020).

System description

The fundamental single flash geothermal systems suggested and propelled by the trans-critical carbon dioxide cycle are shown in Figs. 2 and 3. The system was modeled using EES software. Each system component is employed as a control volume engineering in the simulation technique, and the first and second laws of thermodynamics are applied to it.

According to Fig. 3, during the decompression process, where the pressure decrease occurs at a constant enthalpy, some geothermal fluid enters the system and is changed into a two-phase fluid. The saturated vapor component of the two-phase fluid subsequently enters the separator, which powers the steam turbine. The saturated liquid portion of the separator also enters the vapor generator (VG), which raises the temperature of carbon dioxide gas before the heat exchanger's outlet fluid is redirected to the ground. The gas turbine receives it at the proper pressure and temperature, generating greater power for the entire system. This study differs from earlier ones because the carbon dioxide cycle includes a heat exchanger. 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, improves the system's overall performance. After passing through the heat exchanger and the condenser, the steam turbine's output fluid is piped to the re-injection well and cooled. Table 1 contains a list of the input variables needed to perform the energy and exergy evaluations for the plant. The parameters are displayed in the order that they must be used.

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.



(a)

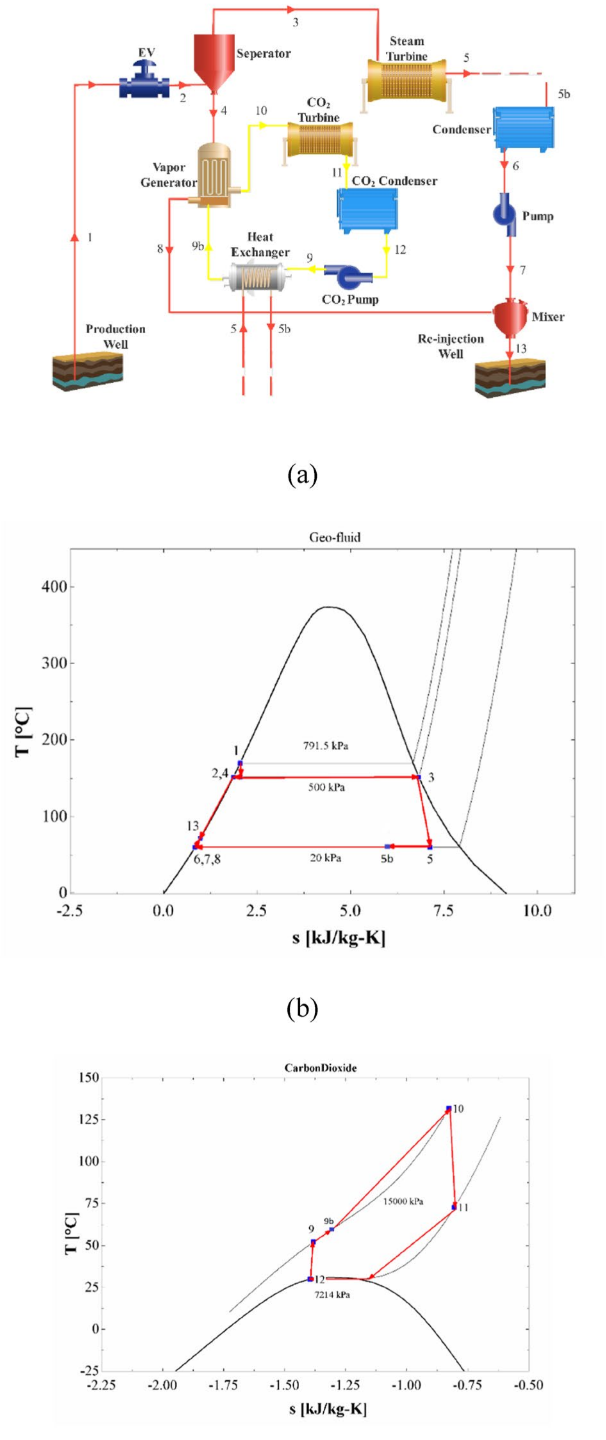
(b)

Fig. 2 **a** Schematic **b** T-s diagram of basic single flash geothermal power plant

Governing equations

The laws of thermodynamics are four physical laws that use the basic physics units (such as pressure, energy, and entropy) to describe thermodynamic systems in thermal equilibrium. The laws above explain how these main units behave in different situations and prohibit some phenomena, such as constant motion. These rules are:

- The zeroth law of thermodynamics: states that if two systems are in thermal equilibrium with a third system, they are in equilibrium with each other.
- The first law of thermodynamics is an isolated system's internal energy is constant and stable. The first law of thermodynamics, also known as the law of conservation of work and energy, states: the change in the internal energy of a system is equal to the difference between the heat given to the system and the work done by the system on the environment with a positive sign.
- Second Law of Thermodynamics: it is impossible to build a motorcycle with no effect other than the continuous transfer of heat from a cold to a hot temperature. Kelvin–Planck statement: it is impossible to make a device that works in one cycle



(a)

(b)

(c)

Fig. 3 **a** Schematic **b**, **c** T-s diagrams of single flash geothermal power plant powered by a trans-critical CO_2 cycle

Table 1 Proposed system initial values (Wang et al. 2015)

Parameter definition	Symbol	Values
Dead state temperature	T_0	25 °C
Dead state Pressure	P_0	100 kPa
Geothermal fluid inlet temperature	T_1	170 °C
Geo-fluid mass flow	$\dot{m}_1$	10 kg/s
Geo-fluid inlet pressure	P_1	Saturated steam
Separator pressure	P_2	500 kPa
Steam turbine output pressure	P_5	20 kPa
CO_2 turbine inlet pressure	P_{10}	15,000 kPa
CO_2 condenser temperature	T_{cond}	30 °C
Turbine isentropic efficiency	η_{tur}	80%
Pump isentropic efficiency	η_{pump}	75%
Evaporator inlet–outlet difference temperature	ΔT_{TTD}	20 °C
Heat exchanger pinch point	ΔT_{PP}	5 °C

and simultaneously has only one heat exchange tank; a heat engine can't continue working without losing heat. Clausius's statement: a refrigerator can't transfer all the energy it receives from a cold source to a hot source during one cycle; rather, some energy is wasted during this process. In other words, the second law of thermodynamics is the path of a process.

- The third law of thermodynamics: the third law of thermodynamics states that when the energy of a system tends to its minimum value, the entropy of the system reaches a negligible value.

The desired cycle is written taking into account the control volume, mass and energy balance for each component of the system according to Eqs. (1) and (2) (Melzi et al. 2021; Pambudi et al. 2021; Parikhani et al. 2021; Saengsikhiao et al. 2021; Yazarlou and Saghafi 2021):

$$\sum \dot{m}_i = \sum \dot{m}_o, \tag{1}$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_o h_o - \sum \dot{m}_i h_i. \tag{2}$$

The subscript i means input, and the subscript o means output. The isentropic efficiency and net power output of each turbine will be obtained from Eqs. (3) and (4):

$$\eta_{\text{Tur}} = \frac{h_i - h_o}{h_i - h_{o,s}}, \tag{3}$$

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

For isentropic efficiency and net operation of each pump can be written:

$$\eta_{\text{Pump}} = \frac{v_i (P_o - P_i)}{h_o - h_i}, \tag{5}$$

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

The net power of the system, as well as the energy efficiency and exergy efficiency of the whole system, will be in the form of Eqs. (7), (8) and (9) (Chen et al. 2021; Mohtaram et al. 2021a; Wang et al. 2015):

$$W_{\text{net}} = W_{\text{tur,steam}} + W_{\text{tur,CO}_2} - W_{\text{pump,steam}} - W_{\text{pump,CO}_2}, \tag{7}$$

$$\eta_{\text{en}} = W_{\text{net}}/Q_{\text{in}}, \tag{8}$$

$$\eta_{\text{ex}} = W_{\text{net}}/E_{\text{in}}. \tag{9}$$

Exergy analysis is obtained by merging the first and second laws of thermodynamics, in which the desired thermodynamic processes of a system are identified by the optimal analysis method of energy systems, as well as a clear knowledge of energy levels. The following hypotheses are considered in the present study (Aali et al. 2017; El Haj Assad et al. 2021a; Sun et al. 2020):

1. All cycle components (as a control volume) work in steady-state conditions.
2. Pressure drop and heat loss in pipelines can be ignored, and changes in kinetic energy and potential in all components are negligible.
3. Turbines have isotropic efficiency of 80%, and pumps have isotropic efficiency of 75%.
4. For the presented analysis, the ambient temperature is 25 °C, and the ambient pressure is 100 kPa.

Definition of dead condition:

- be in thermal equilibrium with the environment (be at the same temperature as the environment).
- be in mechanical equilibrium (be at the same pressure as the environment).
- Its kinetic energy is equal to the kinetic energy of the environment.
- Its potential is equal to the internal energy of the environment.
- Be chemically neutral to the environment.
- It is magnetically and electronically balanced with the environment.

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, the difference between the evaporator tightening point and the evaporator temperature, and the net output power for the under-study cycles are all dependent on these factors.

Genetic algorithm (GA) and Nelder–Mead simplex (NMS) method

The Nelder–Mead simplex technique and the Genetic Algorithm flowcharts are shown in Fig. 4. A genetic algorithm is a search method used in computer science to discover a

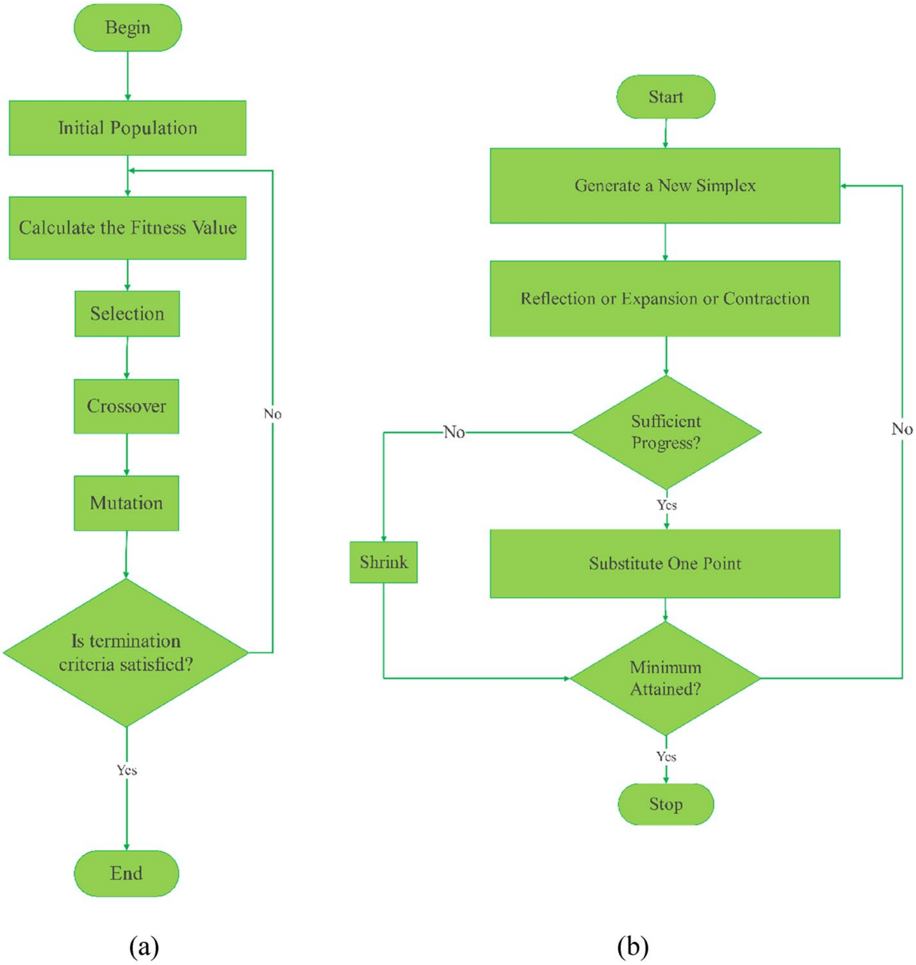


Fig. 4 Flowchart of **a** genetic algorithm **b** Nelder–Mead simplex method (Albadr et al. 2020; Barati 2014)

rough solution to problems involving model optimization, mathematics, and search. The best formula for pattern prediction or matching is found using the genetic algorithm, a special evolutionary algorithm that uses evolutionary biology concepts, including heredity, biological mutation, and Darwin's selection principles. Frequently superior to regression-based prediction methods are genetic algorithms. A programming method known as "genetic algorithm modeling" uses the theory of genetic evolution to solve issues. The inputs to the issue are changed into solutions by a process based on genetic evolution, the solutions are then assessed as candidates by the fitness function, and the algorithm ends if the exit condition of the problem is satisfied. Most of its components are chosen through random processes; generally speaking, it is an algorithm based on repetition. These algorithms include fitting, displaying, selecting, and changing function aspects (Katoch et al. 2021; Mirjalili 2019; Whitley 1994).

A popular numerical technique for determining the lowest or maximum of an objective function in the multidimensional optimization space is the Nelder–Mead simplex approach. It is a direct search technique frequently used for non-linear optimization problems whose derivatives may not be known (based on performance comparison). The Nelder–Mead methodology, on the other hand, is a heuristic search strategy that can converge to non-stationary locations on issues that other approaches can resolve. The Nelder–Mead approach, an expansion of the Spendley et al. method, was presented by John Nelder and Roger Mead in 1965 (Dennis and Woods 1987; Olsson and Nelson 1975; Wright 2010).

EES software

Engineering Equation Solver is software for solving non-linear differential equations. This software was written in 1992 by an American researcher named Klein under cover of F Chart Company. EES software was created after years of teaching thermodynamics and heat transfer courses in mechanical engineering because in these sciences, to solve problems, it is necessary to use the thermophysical properties of materials at the same time as setting equations, and sometimes it is necessary to solve a problem several times with Solve different data. Before the creation of this software, programming in heat and fluid science was done sporadically, but today EES is known as one of the most reliable software for heat and fluid science and is included in many prestigious universities of the world along with courses. Mechanical engineering is used. The main work that EES software does is to solve a set of algebraic equations. Also, this software can solve differential equations, equations with mixed variables, and integral equations. Solving linear and non-linear regression optimization problems and drawing graphs and tables is possible (de Oliveira et al. 2008; Klein 2013; Klein and Alvarado 1999).

Engineering Equation Solver software is one of the most important software in the field of mechanics in solving non-linear equations, as well as reading tables of thermodynamic properties of different gases and psychometric tables, which is very important for mechanical engineers in the field of heat and fluids. This software has two important advantages over other equation-solving software. Firstly, EES automatically identifies and categorizes the equations to be solved simultaneously. This makes the work process very simple for the user and will certainly have the highest speed and efficiency. Second, EES provides the user with a series of functions to calculate the thermophysical properties of materials. The library of mathematical functions and functions of thermophysical properties of materials in EES is very wide, but it may only meet the needs of some people, so it is possible to add arbitrary functions by using programming in C, Pascal and Fortran languages (Yusof and Hassan 2011).

The principles of work in EES are such that first, the desired problem should be analyzed completely, and the necessary equations should be extracted. After extracting the equations, they should be converted into EES language. Then, in the list of variables section, he arranged the names of the variables and their possible units. The program can be executed once if the initial actions are done correctly and the problem can be solved mathematically. If the program encounters a problem during the execution of complex problems, it is necessary to guess values for some variables and solve the problem by trial and error (Klein and Nellis 2013).

Validation

Validation is the process of checking that the software system has the specifications it should have and fulfills the intended purpose of its design. This process must be

Table 2 Validation of the basic single flash geothermal cycle simulation compared with Assad et al.'s results (Assad et al. 2021)

Point	Working fluid	Temperature (°C)		Specific enthalpy (kJ/kg)		Specific entropy (kJ/kg K)	
		This work	Assad et al.	This work	Assad et al.	This work	Assad et al.
1	Geo-fluid	170	170	719.3	719.3	2.042	2.042
2	Geo-fluid	151.9	151.9	719.3	719.3	2.047	2.047
3	Geo-fluid	151.9	151.9	2749	2749	6.821	6.821
4	Geo-fluid	151.9	151.9	640.4	640.4	1.861	1.861
5	Geo-fluid	60.07	60.07	2348	2348	7.122	7.122
6	Geo-fluid	60.07	60.07	251.5	251.5	0.8321	0.8321
7	Geo-fluid	60.13	60.13	252.1	252.1	0.8326	0.8326
8	Geo-fluid	148.5	148.5	625.9	625.9	1.827	1.827

implemented in all stages of system simulation to ensure the validity and accuracy of the inputs and outputs of the computing system. Table 2 shows the validation results:

In this part, the single flash geothermal system is compared with the research of Assad et al. (2021) to confirm the findings with those of earlier studies. In the first section, a graph of steam turbine production power based on the outlet pressure of the pressure expansion valve for the current research model is given, and the results shown show the consistency of the present work and the findings of previous research. This is done to validate the geothermal power cycle.

Results and discussions

Table 3 represents modeling outputs and shows the thermodynamic properties of the Single Flash Geothermal Power Plant combined with the Trans-Critical CO_2 cycle.

Table 4 shows the proposed system's optimization results using the two mentioned algorithms. The column titled Initial Mode in Table 4 shows the output results of the proposed system with the initial data in Table 1. In this case, the total output work of the system is 410.4 kW, and the exergy efficiency is 32.46%.

Three parameters are considered as variables for the optimization process to find the optimal value. These parameters are Separator pressure, CO_2 turbine inlet pressure, and Steam turbine exit pressure. The target parameter for optimization is the exergy efficiency of the whole system. Applying the Genetic Algorithm to the abovementioned three variable parameters, the values of 304.3 kPa, 13,083 kPa and 37.36 kPa are obtained for Separator pressure, CO_2 turbine inlet pressure, and Steam turbine exit pressure, respectively. The total work output of the system in this mode is equal to 316 kW, which is less than the initial mode. But exergy efficiency as a target parameter increases to 39.21% with a significant improvement.

Applying the Nelder–Mead simplex method to the three variable parameters, the values of 326.4 kPa, 12,067 kPa and 22.01 kPa are obtained for Separator pressure, CO_2 turbine inlet pressure, Steam turbine exit pressure, respectively. The total work output of the system in this mode is equal to 459.5 kW, which is more than the initial and genetic algorithms modes. Also, exergy efficiency as a target parameter increases to 36.16% with a good improvement. In summary, for the two optimization processes, the

Table 3 Thermodynamic properties of the single flash geothermal power plant combined with the trans-critical CO_2 cycle

Points	Working fluid	Temperature (°C)	Pressure (KPa)	Enthalpy (kJ/kg)	Entropy (kJ/kg K)	Mass flow rate (kg/s)	Quality	Exergy (kW)
1	Geo-fluid	170	900	719.3	2.042	10	–	1236
2	Geo-fluid	151.9	500	719.3	2.047	10	0.03742	1223
3	Geo-fluid	151.9	500	2749	6.821	0.3742	1	281.7
4	Geo-fluid	151.9	500	640.4	1.861	9.626	0	941.1
5	Geo-Fluid	60.07	20	2348	7.122	0.3742	0.8891	98.55
5b	Geo-fluid	60.07	20	1910	5.81	0.3742	0.7036	78.8
6	Geo-fluid	60.07	20	251.5	0.8321	0.3742	0	3.863
7	Geo-fluid	60.13	500	252.1	0.8326	0.3742	–	4.053
8	Geo-fluid	72.1	500	302.2	0.9802	9.626	–	169.9
9	Carbon dioxide	52.1	15,000	− 186.3	− 1.383	17.2	–	3784
9b	Carbon dioxide	55.7	15,000	− 176.8	− 1.354	17.2	–	3829
10	Carbon dioxide	131.9	15,000	12.53	-0.8275	17.2	–	4403
11	Carbon dioxide	72.72	7214	− 18.03	− 0.8052	17.2	–	3765
12	Carbon dioxide	30	7214	− 202.2	− 1.395	17.2	0	3572
13	Geo-fluid	71.65	500	300.3	0.9748	10	–	173.7

Table 4 Optimization results using genetic algorithm and Nelder–Mead simplex method

Parameters	Definition	Initial mode	Optimal mode using genetic algorithm	Optimal mode using Nelder–Mead simplex method	Units
P_2	Separator pressure	500	304.3	326.4	kPa
P_{10}	CO_2 turbine inlet pressure	15,000	13,083	12,067	kPa
P_5	Steam turbine exit pressure	20	37.36	22.01	kPa
$W_{tur,\ steam}$	The power output of the steam turbine	150.1	194.2	218.1	kW
$W_{tur,\ CO_2}$	The power output of the CO_2 turbine	525.5	606.8	460.8	kW
$W_{pump,\ steam}$	Power consumption of pump 1	0.2436	0.2626	0.2762	kW
$W_{pump,\ CO_2}$	Power consumption of pump 2	274.1	235.6	219	kW
W_{net}	Total net power output	401.3	316	459.5	kW
η_{ex}	Exergy efficiency	32.46	39.21	36.16	%

Genetic Algorithm performs better and improves the exergy efficiency better. However, the advantage of the Nelder–Mead simplex method is that, in addition to improving the exergy efficiency, it also increases the total work output of the system compared to the initial mode.

Exergy analysis, derived from the second law of thermodynamics, is employed in analyzing energy systems and their improvement and creating new cycles (Yari et al. 2015).

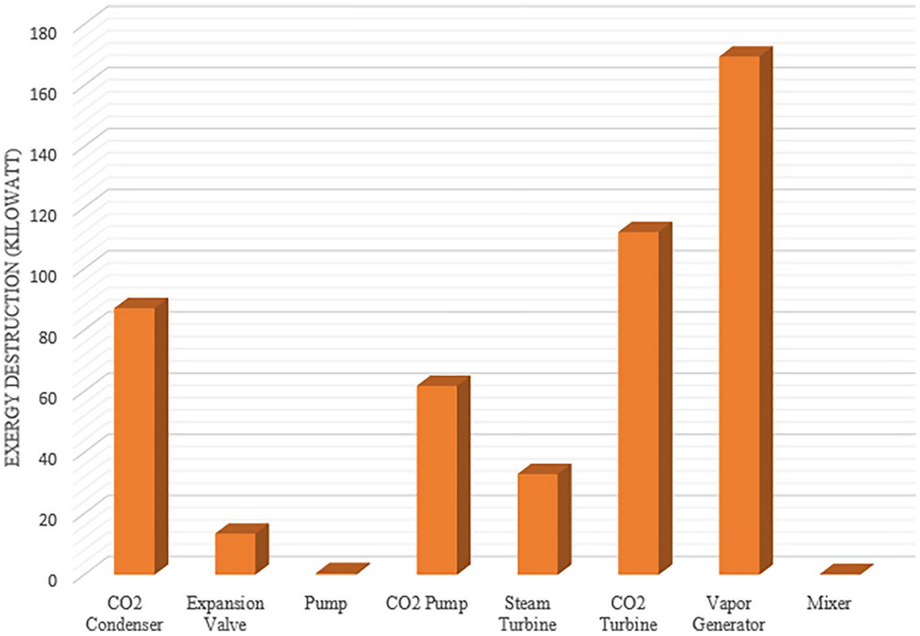


Fig. 5 Exergy destruction amounts of the components of the system

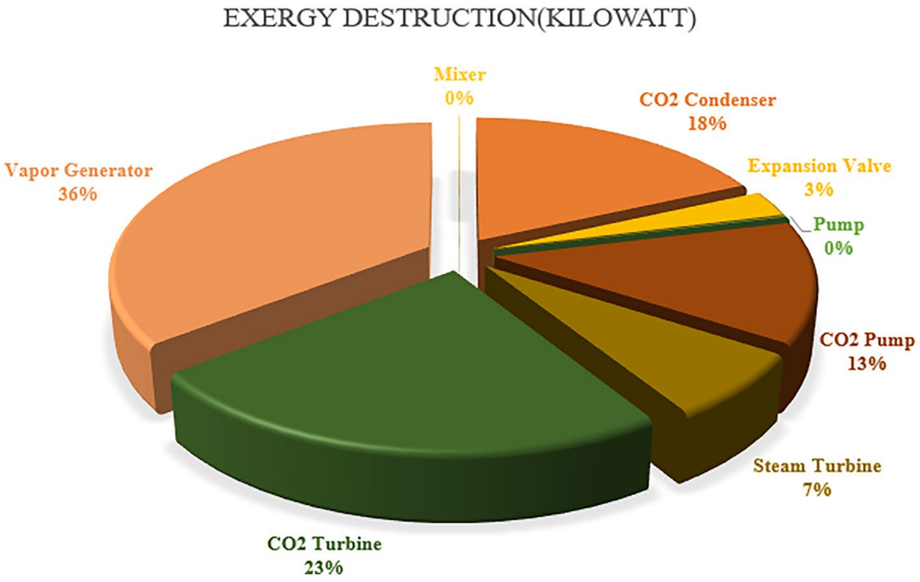
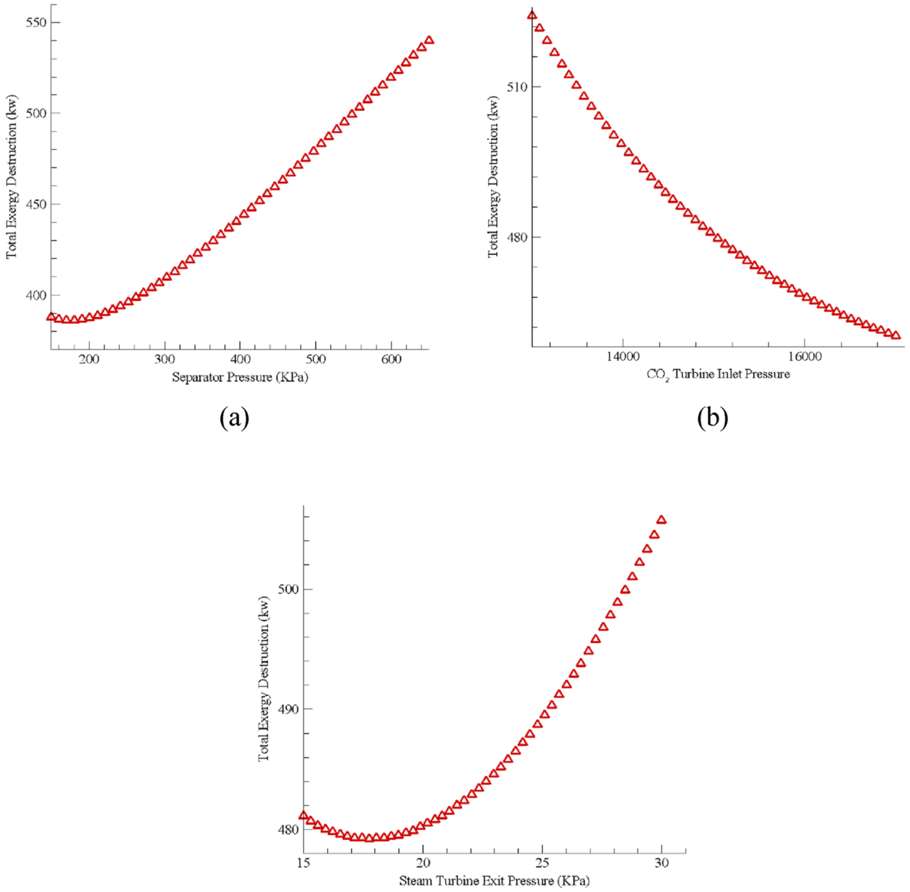


Fig. 6 Exergy destruction ratio of the components of the system

Figure 5 displays the percentages of energy destruction for each recovery system component. The percentages of each component's exergy destruction are shown in a pie chart in Fig. 6. Most exergy destruction occurs in the vapor generator, which accounts for over 36% of the proposed system's total exergy destruction with an exergy destruction rate of roughly 167 kW. This suggests that the fluids in this component have a wide temperature range. The next two components of the system that consume the most energy are the CO_2 turbine and CO_2 condenser. Energy destruction in the separator and single



(a)

(b)

(c)

Fig. 7 Exergy destruction changes of the total system with respect to the **a** separator pressure **b** CO_2 turbine inlet pressure **c** steam turbine exit pressure changes

flash cycle condenser is minimal and is considered zero in this calculation. Additionally, as seen in both diagrams, the single flash cycle pump and mixer's exergy destruction is negligible compared to other parts. As it turns out, the carbon dioxide cycle part's component suffers from exergy destruction significantly more severe than the component of the single flash cycle, which may be caused by the carbon dioxide cycle running in a trans-critical condition.

Combining various yet thermodynamically compatible cycles is one method for enhancing the performance of power generation cycles. Trans-critical carbon dioxide cycles have advantages over other power generation methods when paired with other cycles.

The impact of separator pressure adjustments on the system's overall exergy destruction is depicted in Fig. 7a. The total energy destruction first has a lowering trend and reaches its minimum value around 188 kPa with an increase in separator pressure from 150 to 650 kPa, then has an increasing rate and continues to rise. The exergy destruction of the entire system always decreases with an increase in pressure from 13,000 kPa to 17,000 kPa, as shown in Fig. 7b, which illustrates the impact of carbon dioxide turbine input pressure changes on the exergy destruction of the entire system. As a result, and from the perspective of exergy destruction, increasing the inlet pressure of the carbon dioxide turbine positively impacts the system's performance. When the steam turbine output is increased from 15 to 30 kPa in Fig. 7c, like in Fig. 6a, the quantity of energy destruction initially achieves the minimum value at 18 kPa and subsequently increases.

Research limitations and future works

Researchers must contend with restrictions in all of their work, some of which become apparent right once. One of the fundamental foundations of research is the availability of data and information. In this subject, some issues make it difficult to access research services like books, publications, statistics, databases, etc. Due in part to the absence of any of the abovementioned research services and in part to the erroneous cultural perception of these situations as being private, people and institutions have refused to share their findings with others. On the other hand, undesirable factors that may arise from unique research designs and methodologies frequently compromise the internal and external validity of the study in various ways. It is important to understand that it is hard to entirely regulate or eliminate these influences in behavioral science study. However, researchers make every effort to anticipate, recognize, and identify these effects as much as possible and take all necessary measures to minimize them. Both subsurface and power plant technology address the environmental challenges associated with geothermal development. Research and development into a novel, efficient, and inexpensive technologies will enhance security and environmental integrity as geothermal energy, and power use grows. The following are the main issues with geothermal projects (Moses Jeremiah Barasa 2019):

- Restrictions on the use of places and properties brought about by encroachment on private land, field crossings, deforestation, excavations, path modification, and road and power plant development.
- Leveling of work zones to build drilling yards, store supplies and equipment, and install plants, interfering with the terrain and geography of activity zones
- The noise produced by the movement of large trucks, the motors of drilling rigs, the testing of geothermal wells, the manufacturing of fluids, and other field engineering and non-engineering processes during exploration and drilling.
- Disposal of waste materials produced during and after drilling, including mud, cuttings, oil, and various process fluids.
- Well, blowouts under pressure that are not controlled.
- Scaling of pipes and other surfaces results from hot water leaks, water–steam mixture leaks, and turbine condensate leaks.
- Soil contamination from salts percolating into water streams and soil pollution
- The release of used water after it has been separated from steam into the soil, water channels, lakes, and lagoons;
- The injection of condensate and wastewater causes pollution into fresh aquifers.
- The toxic gases carbon dioxide, hydrogen, and steam containing mercury, azimuth, and boron are released into the atmosphere.

- Acid showers are caused by gaseous emissions such as carbon dioxide, nitrogen oxides, and sulfur dioxide from processes such as fuel burning during drilling and field development.
- The injection of water causes seismic activity in wells.
- Surface subsidence or sinking, as seen at the Wairakei power plant in New Zealand, resulted from decreased reservoir pressure brought on by an overabundance of fluid.
- Heat pollution, especially in the vicinity of power stations.
- The visual impact of trenches, platforms, drilling rigs, barracks, sheds, plant equipment, power lines, steam pipes, water pipelines, and other structures.
- Cauterization of drilling yards as a result of the usage of cement in technical applications such as drilling.

Another challenge is the high initial costs of developing a geothermal energy system. This is a major problem for the oil and gas industry, especially in the current situation. The next thing is uncertainty in this area. There is no need to spend millions of dollars to determine whether or not there is an energy source for wind and solar development. Everyone sees the sun in the sky and feels the wind, but the temperature and permeability of a rock 3 km underground are not like this. These are the challenges that geothermal energy must overcome to reap its benefits—durability, sustainability, and non-pollution. Wind and solar energy are cheaper, but they depend on environmental conditions, are not continuous, and have a limited lifespan. In the discussion of geothermal energy, the lifetime of the well is unlimited, and there is no need to recycle it. Regarding future research for researchers about the studied system, the following suggestions are provided:

- Providing two-variable optimization of the proposed system for a comparative study with the results of the present work.
- Exergeoeconomic and exergeoenvironmental analysis of the current system and also advanced exergy analysis of the system.
- Providing solar−geothermal hybrid systems increases the efficiency and higher reliability factor of the provided system.

Conclusions

The working fluid passes through the subcritical and supercritical phases in a closed thermodynamic cycle known as a trans-critical cycle. In power cycles, the working fluid is kept in the liquid region during compression and vapor and supercritical regions during expansion. The ultra-supercritical steam Rankine cycle is a typical trans-critical cycle that uses water as the working fluid and is used to produce energy from fossil fuels. Another example of typical trans-critical cycle uses for power production is organic Rankine cycles, which are particularly well adapted to exploiting low-temperature heat sources, such as geothermal energy, heat recovery applications, or waste-to-energy plants. By definition, trans-critical cycles, as opposed to subcritical cycles, benefit from greater pressure ratios, a characteristic that ultimately leads to higher efficiency for the bulk of the working fluids. Trans-critical cycles can obtain more particular works since the compression work is only marginally more necessary than other tasks since supercritical cycles are a potential alternative to trans-critical ones. This exemplifies the enormous potential of trans-critical cycles to realize the objective of producing the greatest amount of power (quantifiable in terms of the effort specific to the cycle) with the least amount of expense (measurable in terms of spent energy to compress the working fluid). Instead, novel trans-critical cycles should employ a working fluid with a critical temperature close to the surrounding temperature. Due to its favorable critical circumstances, carbon dioxide is chosen. The critical point of carbon dioxide is 31 °C, which is excellent for trans-critical applications since it is reasonably midway between conventional refrigeration applications' hot and cold sources. The combination of trans-critical carbon dioxide cycles with other energy systems, such as solar and geothermal energy, will increase the overall efficiency of the cycle. Also, nowadays, many applications with the potential to recover wasted heat, such as exhaust gases from piston engines, cement kilns or heat treatment furnaces, are often combined with cycles such as Organic Rankine, Reverse Brayton, Kalina, Stirling, Reverse Brayton-Organic Rankine, etc. to convert wasted heat into mechanical power.

This study has explored the energy and exergy of a combined power production system (combined single flash geothermal cycle with trans-critical carbon dioxide cycle) in both its optimal and initial forms. Exergy efficiency was equivalent to 32.46% in the initial mode, and after the Genetic Algorithm, this number climbed to 39.21%. The exergy efficiency of the Nelder–Mead simplex method has grown from 32.46 to 36.16%. The Nelder–Mead simplex method is less efficient than utilizing a Genetic Algorithm.

The proposed cycle was then examined from the component exergy destruction rate perspective. The exergy destruction on the carbon dioxide side was greater than in the single flash cycle. The vapor generator with 36%, the CO_2 turbine with 23% and the CO_2 condenser with 17% exergy destruction of the whole system had the highest exergy destruction among the system components. Exergy destruction in the single flash geothermal cycle condenser and the separator is negligible and is considered zero here. Also, the amount of exergy destruction in the single flash geothermal cycle's pump and mixer is insignificant compared to other components.

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Author contributions
JH: resources, formal analysis; AMA: writing, review and editing, formal analysis; SME, JLGA: review and editing; YA: conceptualization, validation, writing, original draft, visualization. All authors have been directly involved in the planning, execution, or analysis of this study. All authors read and approved the final manuscript.

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Declarations

Ethics approval and consent to participate
This research did not contain any studies involving animal or human participants, nor did it take place in any private or protected areas. No specific permissions were required for corresponding locations.

Consent for publication

I, the undersigned, give my consent for the publication of identifiable details, which can include a photograph(s) and/or videos and/or case history and/or details within the text ("Material") to be published in the above Journal and Article.

Competing interests

The authors declare no competing interests.

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