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Energy and exergy and economic (3E) analysis of a two-stage organic Rankine cycle for single flash geothermal power plant exhaust exergy recovery

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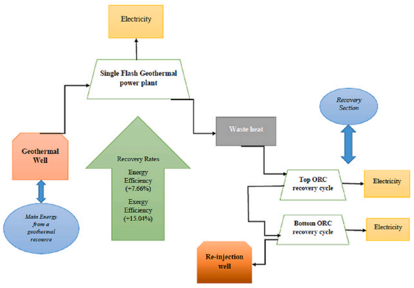
GRAPHICAL ABSTRACT



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ABSTRACT

A two-stage ORC (Organic Rankine Cycle) is being proposed for the recovery and utilization of low-grade heat from single flash geothermal power plant exhaust flue fluids. The working fluids for two-stage the recovery system are R227ea and R116. The impact of essential design parameters such as inlet temperature of the cycle, ambient temperature, geothermal turbine inlet pressure, geothermal condensation temperature on system performance are investigated using thermodynamic mathematical models regarding energy and exergy efficiencies as the objective function. The addition of the recovery section to the base cycle improves the thermal efficiency from 0.2023 to 0.2178, a 7.66% improvement in this critical metric. Furthermore, the exergy efficiency rises from 0.55044 to 0.5803, representing a 15.04% boost in exergy efficiency. Furthermore, the system's overall output rises from 7690 kW to 9898 kW, representing a substantial gain of 28.71%. The suggested recovery system's cycle has a lower LEC than a single flash geothermal cycle from an economic standpoint. LEC Reduced from $ 0.125 per kilowatt to $ 0.108 per kw, a cost savings. As a result, including a recovery section in the basic single flash geothermal cycle will significantly improve system performance.

Nomenclature

Abbreviations

E	Exergy [kW]
e	Specific Exergy [kW/kg]
h	Specific Enthalpy [kJ/kg]
$\dot{m}$	Mass flow rate [kg/s]
P	Pressure [MPa]
$\dot{Q}$	Heat flow rate [kW]
s	Specific Entropy [kJ/kg.K]
T	Temperature [Degree Celsius]
W	Power output [kW]

Greek Letters

η	Efficiency
ΔT	Temperature Difference

Subscripts

0	Dead State
cr	Critical
x	Quality [−]
v	Specific volume [m^3/s]
0	Dead State
$cond$	Condenser
ex	Exergy
en	Energy
d	Destruction
E	Geothermal Stream
f	Fluid
g	Gas
geo	Geothermal
net	Network
P	pump
sep	Separator
T	Turbine
DD	Pinch Point

1. Introduction

Increasing energy demand, limited sources of fossil fuels and their harmful environmental effects (including global warming) have increased efforts to use clean energy sources. Among renewable energy sources, geothermal energy has a special place due to its vast resources throughout the earth [1]. Nowadays to improve energy efficiency in the industrial sectors, heat recovery technologies have been continuously developed and improved using independent and combined cycle settings. Most of the energy challenges, including resources, demand and supply, as well as their applications, have always been a global issue. Countries around the world, especially developed ones, have allocated significant budgets to conduct contemporary assessments on energy. Operational plans are being developed around the world, including opportunities for innovation and progress. Many types of research have lately been undertaken on the use of low and clean heat sources, including renewable energy sources, to minimize environmental impacts. Geothermal energy among renewable energies due to its operation in all seasons and 24 h a day, as well as the low amount of undesirable gases produced, is very popular. Due to the production of renewable energies spread in places remote from power transmission networks, it is nearly difficult to implement appropriate regulations for the use of these forms of energies, independent of the impediments to their growth [2].

Energy loss, energy-saving and low-efficiency problems, attract attentions more recently and become an area of research and development importance. The use of the Organic Rankine Cycle (ORC) is one of the proposed robust applications to increase energy consumption and other environmental heat dissipation emissions recovery system applications [3]. In ORC, the working fluid is replaced in the traditional steam cycle. The boiling point of temperature and pressure increases lower. The pressure of organic fluids is better adapted to medium and low temperatures. Compared with vineyard water resources, power generation, components and procedures are simple to start, do not participate in operations, easy to maintain, long life, low application cost and availability of various sources. Ineffective steam cycles and organic fluid defects (i.e. ignition, toxicity, environmental issues, and cost) are the main errors of this technology [4]. ORC is a well-known power plant and it has proven to be a valuable system for converting thermal energy into mechanical energy for many years. ORC is a potential alternative to efficiently generate energy from low-temperature heat sources. Although the simple configuration of ORC can be seen as its advantage due to its simplicity, reliability and flexibility [5].

Alibaba et al. [6] After building and optimizing a geothermal power plant to supplement concentrated solar power (CSP), combined 4E (Energy. Exergy, Economical and Environmental) research was conducted. Autonomous geothermal cycles (mode 1) and combined solar geothermal cycles (mode 2) are designed to generate heating and cooling power within buildings. According to both study and economic analysis of the emergence of independent geothermal cycles, the ORC condenser has the lowest value, with the highest value due to the heat released by the impact of the turbine blades. The evaporator and turbine had the greatest amounts of auxiliary and environmental elements in the combined geothermal-solar cycle.

Shuozhuo et al. [7] proposed a novel data-driven technique for predicting out-of-system performance quickly and accurately, allowing for the realistic design of a combined geothermal-solar energy system's durability. Prepare for this challenge by training and verifying an artificial neural network (ANN) to predict the hourly performance of a hybrid system based on the Rankin Organic Cycle (ORC) throughout a 30-year lifetime. The trained ANN is used with a multi-objective optimization methodology to discover the best system design. The results demonstrate the efficacy of an ANN-based strategy for the active design of a hybrid system, which may significantly cut computation time while retaining a 2% accuracy. In addition, the new approach has been shown to be 17% and 14% more efficient in improving life expectancy (E_{tot}) and net present value (NPV), respectively.

Weng et al. [8] studied power generation with geothermal heating systems made from a combination in which heating is provided by radiant floor heating systems, generating energy in the ORC. It uses comprehensive thermodynamic, kinetic economics, and kinetic environmental models of the system to investigate the cost of capital and the environmental impact of system components. To evaluate system performance, the superheat of the organic liquid and the input pressure of the ORC turbine are selected as variables. Multi-purpose optimization is applied in the system to obtain the maximum active power of the system, the minimum balance cost per unit of the accelerator and the minimization of environmental impact per unit of the accelerator of the system. The results make it clear that increasing the hydraulic oil heat input pressure of an ORC turbine has an undue effect on the production of the turbine while increasing the heat source. Below 11 °C and 833 kPa, the ORC Turbine Input cycle is an additional flow system with a net output of 1.19 MW, a cost of 4.80$ per gigabyte per unit.

Nasruddin et al. [9] reviewed the multipurpose optimization of two geothermal power plants in Anparas, West Sulawesi, Indonesia, based on the economic, exergo-economic and exergo-environmental assessment of dual geothermal plants. This study compares and contrasts two binary cycle systems. The ORC, which uses isopentane as the working fluid, and the Kailna Cycle (KC), which together generate energy with ammonia and water. MATLAB was used with Engineering Equations Solver (EES) software to simulate two binary systems and optimize the three target functions using an evolutionary algorithm strategy. The ORC system is the most efficient and has an exergy efficiency of 82.12%, a price of 8.19 cents/kWh, and a total environmental impact of 282.29 mPt/s.

Abdolalipouradl et al. [10] researched and proposed four innovative configurations: Single Flash-ORC (SF-ORC), Double Flash 1-ORC (DF1-ORC), Double Flash 2-ORC (DF2-ORC), and Triple Flash-ORC (TF2-ORC) were used to produce electricity in two wells in this field (TF-ORC). The configurations are assessed in terms of thermodynamics and exergo-economics. A full parametric study of the suggested ORC configurations was also carried out, taking into account various operating fluids. Furthermore, optimization is carried out to optimize the power provided by the wells. Under optimum conditions, DF1-ORC generates 4.03%, 1.32%, and 1.2% more energy than SF-ORC, DF2-ORC, and TF-ORC, respectively. Extra-economic analysis shows that with R123 working fluid, SF-ORC achieves maximum economic performance at a specific power cost of 3.62$/GIG. The thermodynamic and extra-economic performance of DF1-ORC is compared with that of previous similar studies, revealing the superiority of the proposed cycle.

Wenge et al. [11] developed a geothermal heating and power generation system that transfers heat using Organic Rankine Cycle and radiant underfloor heating technologies. The system's comprehensive thermodynamic, exergo-economic, and exergo-environmental models are used to investigate the cost of capital and environmental impact of the components of the system. Overheating of the organic fluid and ORC turbine input pressure were selected as variables to measure the performance of the system. The results show that increasing the temperature of the working fluid and the inlet pressure of the ORC turbine reduces the capacity of the Organic Rankin Cycle turbine and increases the heat. The ORC turbine input is an additional flow system with a net output of 1.19 MW, a leveling cost of 4.80$ per gallon, and environmental impacts of 16 mAh/GJ below 11 °C and 833 kPa.

Lebbihiat et al. [12] discuss the history of geothermal energy in Algeria, as well as its current use, practices, and potential. Algeria has several low enthalpy geothermal resources that can be integrated into the country's national energy network. Balneology is Algeria's most common use of geothermal energy, accounting for about 82% of total geothermal power usage. This paper explains the elements that influence the growth of geothermal energy in Algeria and proposes a growth plan as well as some initiatives that might help this important energy source grow.

Ozturk and Dincer [13] introduced a new integrated system that uses geothermal energy as a renewable energy source. It was made and evaluated thermodynamically and its performance was evaluated using various criteria. According to the survey, the energy efficiency of the integrated plant is 59.93%, but the exergy efficiency is 57.18%, which more precisely indicates practicality. Finally, the results of the exergy evaluation at other sub-plants of the geothermal-based combination plant suggest that the Kalina cycle and hydrogen production plants have the highest exergy destruction rate.

Wang et al. [14] introduced a new flash binary geothermal source-based combined cooling and power generation system. The binary subsystem of the proposed equipment is an internal combination of an ORC and an ejector refrigeration cycle. Examine the feasibility of the proposed system in terms of energy and exergy. The optimization method provides some important information such as total cooling capacity, net output power, energy efficiency, and increased exergetic efficiency. The optimal parameters of the pentane (0.533)/butane (0.467) combination were found with a cooling capacity of 330.7 kW, a net output of 1.687 MW, thermal efficiency of 19.20% and an exergetic efficiency of 53.27%.

Yilmaz [15] presented an integrated facility with geothermal energy support for heating, cooling, electricity, hot water generation and hydrogen production. ORC-1 operating on *n*-pentane and ORC-2 operating on *n*-butane are the two ORCs of the modeled system. Thermodynamic and environmental impact assessments are conducted to determine plant performance and reduce greenhouse gas emissions. An environmental impact assessment is conducted to determine the impact of greenhouse gases as a result of the use of non-renewable energy-based fuels for power generation in the proposed model. According to the analysis results, the total energy performance and the exergy performance of the system under investigation were calculated to be 63.28% and 55.99%, respectively. The two sub-plants of the modeled system, ORC-1 and ORC-2, provide energy efficiencies of 22.31% and 25.18%, respectively. 806.4 kW, 758 kW and 9.036 kg/h are the heating, cooling and hydrogen production rates, respectively.

ORC has proven to be a promising low-temperature heat recovery technology [16]. ORC applications cover a wide range of fields, including solar energy [17,18], geothermal energy [19,20], diesel engine waste heat [21,22], industry [23] and biomass energy [24,25]. In addition, a lot of research on ORC's working fluid selection [26], system configuration [27], operating parameters [28] and specific components [29,30] has been carried out.

Environmental scientists are concerned about climate change because of its negative consequences, such as glacier retreat, altered animal and plant habitats, more intense heat waves, and rising sea levels [31]. The increasing growth of the human population, along with a scarcity of energy sources, has raised the relevance of understanding energy issues in recent decades. These research span a wide range of subjects, including energy storage instruments, power generating system optimization, and renewable energy sources [32]. Several research has focused on reducing greenhouse gas emissions such as carbon dioxide, carbon monoxide, and nitrogen oxides (NOx). Because energy use, particularly fossil fuel consumption, contributes significantly to the production of greenhouse gases, several renewable energy solutions with reduced emissions have been developed in recent years [33]. Large volumes of waste heat, such as exhaust gases from combined cycle and power plants, have been discharged into the atmosphere in recent years, polluting the ecosystem. As we have seen, the ORC technology is one of the most promising technologies for utilizing the energy lost in geothermal power plants, and this technology is one of the most cost-effective ways to improve system efficiencies. In recent years, numerous studies have been carried out on the recovery of residual heat from geothermal power plants. Based on the previous research background, the research gap around waste heat recovery from the two-stage ORC single flash geothermal power plant has been identified. In this paper, a two-stage ORC (Organic Rankine Cycle) is recommended to collect and use the low-temperature lost heat of the exhaust fluid of a single flash geothermal power plant. For systems, R227ea and R116 are working fluids. The impact of critical design parameters such as turbine intake pressures, working fluid mass flow rates, and evaporator output steam percentages on system performance are studied using thermodynamic mathematical models using thermodynamics and exergy as the objective function.

In this study, a re-injection fluid stream with a single flash geothermal power plant cycle was selected as the low-temperature heat source. However, the heat source is not limited to the waste heat from the geothermal source. The cycle can also be used for other waste heat and renewable energy uses, such as industrial wastewater hot water, fossil power plant resources and solar panels.

The main objectives of the current research are:

- To simulate and analyze the two-stage organic rankine cycle for exergetic recovery of flue gases from single flash geothermal power plants
- Make a full comparison of the operating conditions of the basic cycle and the main proposed recovery cycle.
- Investigate changes in key parameters related to energy and exergy efficiency.
- Optimizes the system based on the sensitivity method, finds the best system performance.

- Perform a comparison of the two cycles from economic points of view.

After the introduction, the rest of the work is structured as follows:

The second section introduces the materials and methods, including the thermodynamic models in the second section and the underlying equations in the third section, the third section mathematically demonstrates the energy and exergy analysis of the proposed recovery power plant, and the fourth section proposes the recovery power plant's analysis. The fifth part shows the simulation results graphically to see the influence of the most important parameters on the performance of the power plant. The last part shows the main results obtained in this paper.

2. Materials and methods

2.1. System description

Fig. 1 illustrates the components of a single flash geothermal power plant with a two-stage Organic Rankine Cycle recovery, including the expansion valve, separator, steam turbines, condensers, and pumps. The geofluid (clean water) from the production well (mode E1) passes through the expansion valve (Ex 1) as a saturated liquid, lowering the pressure and temperature and causes a two-phase flow. The two-phase current (mode E2) enters the adiabatic separator (S-1) at the steam separation point and is fed to the steam turbine (T-3). For low-temperature applications, the liquid that remains in the separator (Mode E7) can be utilized as a waste heat source. The steam expands and condenses in state E4, a two-phase situation, before condensing in state E5 in the condenser (C-3). After condensation, the condenser outlet enters the pump (P-3) and is pumped to the mixing point with the outlet fluid from the separator (E8).

The two-stage Organic Rankine Cycle consists of an upper cycle that uses R227ea as the working fluid and a lower cycle that uses R116 as the working fluid. The number 1234561 indicates the upper cycle. Pump 1 (P-1) increases the cold liquid pressure R227ea to the required pressure (mode 2) before absorbing heat from the outlet fluid of the single flash geothermal cycle. It saturates in the first heat exchanger (HE-1B), but overheats in the second one (HE-1A). The enthalpy of steam R227ea is transformed to electricity in turbine 1 (T-1). Low-pressure steam goes through the third heat exchanger (HE-1C) before being transported to condenser 1 (C-1) for liquefaction. 7-8-9-10-11- 12-13-7 can be used to specify the lower cycle. The exhaust vapor from turbine 1 (T-1) and the geothermal waste liquid stream (E10) drive the lower cycle. In the bottom cycle, the regenerator (HE-2B) is employed to recover the thermal energy of the turbine 2 (T-2) effluent. The low-temperature heat source in this study was an exhausted geofluid from a combined cycle power plant. Industrial heat loss, on the other hand, is not the only source of heat. Industrial hot water losses, other geothermal resources and other waste heat and renewable energy sources such as solar can also be used in this cycle.

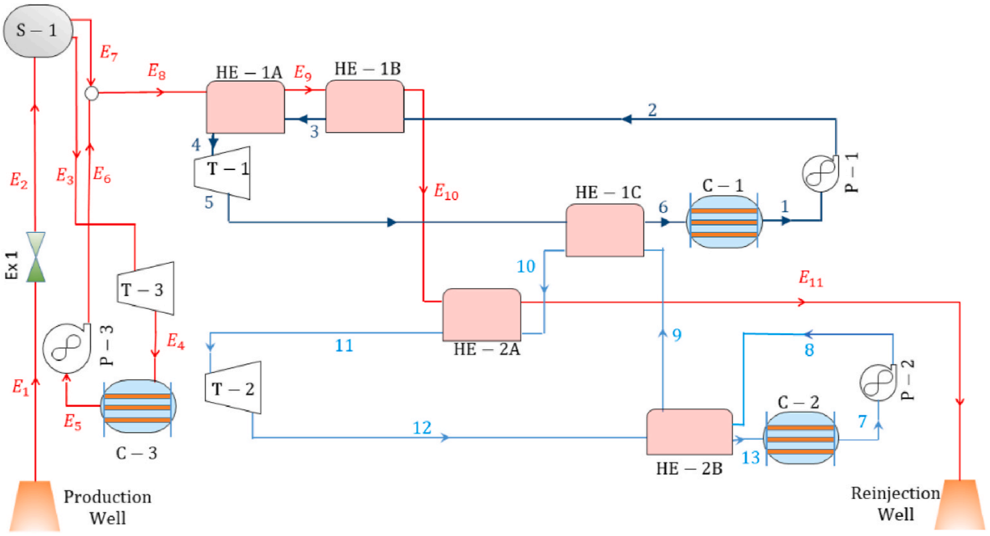

Fig. 1. Schematic diagram of the single flash geothermal power plant with two-stage ORC recovery.

2.2. ORC working fluid

Thermodynamic features of working fluids have an impact on the system's efficiency, performance, and environmental characteristics. The combination of R227ea and R116, according to Xiaodi et al. [8,] has one of the best performances. R227ea and R116, on the other hand, aren't the best because there are so many distinct working fluids and their combinations. The purpose of this study is to investigate a unique method of recovering energy from geothermal power plant losses. The functionalities of various working fluid mixtures are equivalent. As a result, without a complete comparison in terms of working fluids, the combination of R227ea and R116 has deemed representative.

The working fluids R227ea and R116 were chosen as the top and bottom cycles, respectively, to manage temperature, provide a high-performance system, ensure safety, and have a minimal negative environmental impact. As previously stated, the physical qualities of working fluids are selected. Table 1 contains this information. The GWP (Global warming potential) is calculated as a carbon dioxide factor.

Engineering Equation Solver (EES) software and a genetic algorithm optimization procedure will be used to model the systems. Fig. 2 shows the entire simulated thermodynamic optimization process for a geothermal power plant.

2.3. Governing equations

Mass flow rate balance equations for the system are:

$$\dot{m}_{E1} = \dot{m}_{E2} = \dot{m}_{E8} = \dot{m}_{E9} = \dot{m}_{E10} = \dot{m}_{E11} \tag{1}$$

$$\dot{m}_{E3} = \dot{m}_{E4} = \dot{m}_{E5} = \dot{m}_{E6} = x_{E2}\, \dot{m}_{E2} \tag{2}$$

$$\dot{m}_{E7} = (1 - x_{E2})\dot{m}_{E2} \tag{3}$$

where x_{E2} is the vapor quality at state E_2. About the two-stage organic Rankine cycle mass flow rate equations follow:

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_3 = \dot{m}_4 = \dot{m}_5 = \dot{m}_6 \tag{4}$$

$$\dot{m}_7 = \dot{m}_8 = \dot{m}_9 = \dot{m}_{10} = \dot{m}_{11} = \dot{m}_{12} = \dot{m}_{13} \tag{5}$$

2.3.1. Energy balance

The energy rate balance equation for a particular enthalpy related system instrument is:
Expansion valve:

$$h_{E1} = h_{E2} \tag{6}$$

where

$$h_{E1} = h_f\ (T_{E1}) \tag{7}$$

The steam quality at state E_2 can be present as

$$x_{E2} = \frac{h_{E2} - h_f}{h_{fg}} \tag{8}$$

Calculate the mass flow rates of saturated vapor and saturated liquid leaving the separator.
Separator:

Table 1
The ORC working fluids' physical qualities [35].

Cycle	Top Cycle	Bottom Cycle
Working fluid	R227ea	R116
Chemical formula	CF3CHFCF3	CF3CF3
Tcr (K)	374.9	293.03
Pcr (MPa)	2.925	3.042
Tcr (0.1 MPa)	194.85	256.45
ODP	0	0
DWP	3500	11900
dT/dS	>0	∞

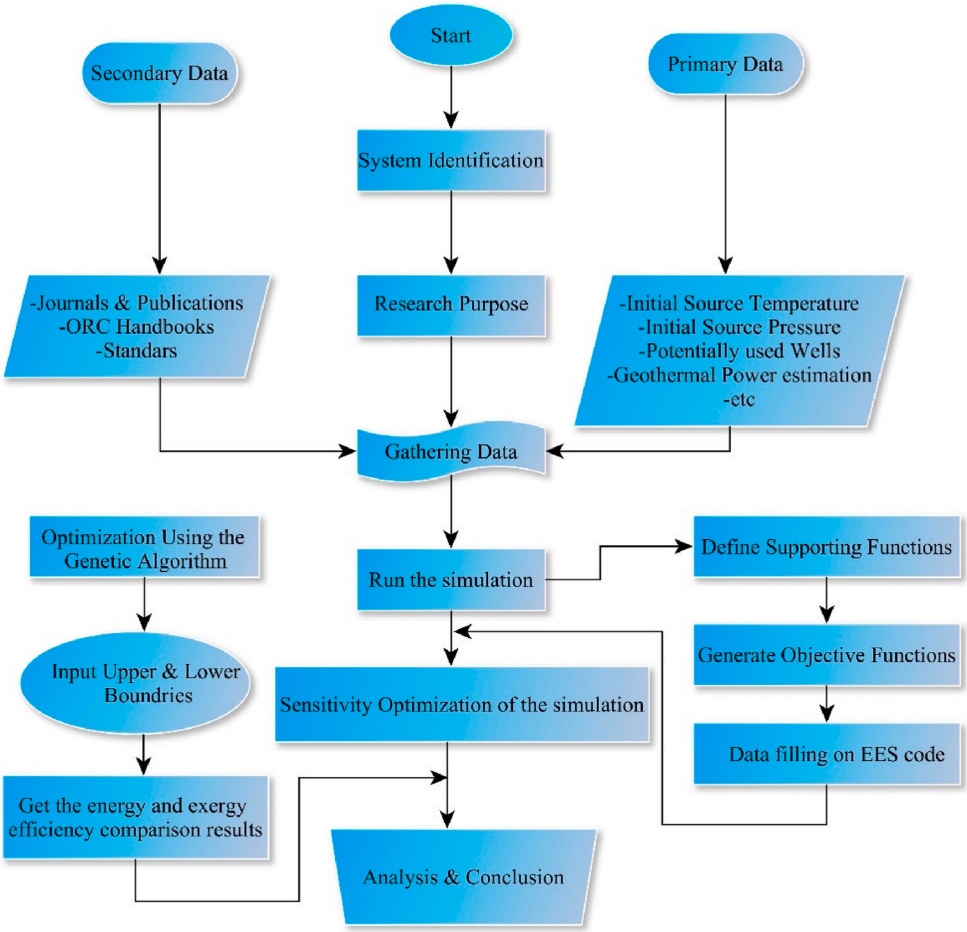

Fig. 2. Workflow diagram.

$$\dot{m}_{E2}h_{E2} = \dot{m}_{E3}h_{E3} + \dot{m}_{E7}h_{E7} \tag{9}$$

where

$$h_{E3} = h_g\ (T_{sep}) \tag{10}$$

and

$$h_{E7} = h_f\ (T_{sep}) \tag{11}$$

Steam turbine:

$$\dot{W}_{T-3} = \dot{m}_{E3}(h_{E3} - h_{E4}) \tag{12}$$

The specific enthalpy of state E_4 can be calculated using following equations:

$$x_{4s} = \frac{s_{E4s} - s_f}{s_{fg}} \tag{13}$$

$$s_{E4s} = s_{E3} = s_g\ (T_{sep}) \tag{14}$$

$$h_{E4s} = h_f + x_{E4s}\ h_{fg} \tag{15}$$

$$h_{E4} = h_{E3} - \eta_{T3}(h_{E3} - h_{E4s}) \tag{16}$$

where η_{T3} is the isentropic efficiency of the steam turbine 3 and s denotes the isentropic state.

Condenser:

$$\dot{Q}_{c3} = \dot{m}_{E4}(h_{E4} - h_{E5}) \tag{17}$$

where $h_{E5} = h_f\ (P_{cond3})$.

Pump:

The following formulae can be used to calculate pump work:

$$s_{E6s} = s_{E5} \tag{18}$$

$$h_{E6s} - h_{E5} = v_{E5}(P_{E6} - P_{E5}) \tag{19}$$

$$\eta_{P-3} = \frac{h_{E6s} - h_{E5}}{h_{E6} - h_{E5}} \tag{20}$$

where η_{P3} is the isentropic efficiency of the pump and v_{E5} is the specific volume at state E_5.

$$\dot{W}_{P3} = \dot{m}_{E5}(h_{E6} - h_{E5}) \tag{21}$$

2.3.2. Exergy analysis

State i's particular flow exergy may be written as

$$e_{xi} = (h_i - h_o) - T_o(s_i - s_o) \tag{22}$$

as well as the associated exergy rate

$$\dot{E}_i = \dot{m}_i[(h_i - h_o) - T_o(s_i - s_o)] \tag{23}$$

Exergy rate balances for each component may be stated as follows in terms of flow exergy and exergy destruction rates:

Expansion valve:

$$\dot{E}_{E1} = \dot{E}_{E2} + \dot{E}_{d,v} \tag{24}$$

Separator:

$$\dot{E}_{E2} = \dot{E}_{E3} + \dot{E}_{E7} + \dot{E}_{d,s} \tag{25}$$

Steam turbine:

$$\dot{E}_{E3} = \dot{E}_{E4} + \dot{W}_{T3} + \dot{E}_{d,T3} \tag{26}$$

By applying Equations (12) and (23), the exergy rate destruction of the turbine, $\dot{E}_{d,T3}$, is obtained as

$$\dot{E}_{d,T-3} = \dot{m}_{E3} T_o(s_{E4} - s_{E3}) \tag{27}$$

where T_o is the ambient temperature (298.15 K).

Condenser:

Table 2

ORC working fluids' physical properties.

Parameters	Formula	Ref.
Power generated by the turbine	$W_{T-1} = \dot{m}_{ts}(h_4 - h_{5s})\eta_{T-1} = \dot{m}_{ts}(h_4 - h_5)$ $W_{T-2} = \dot{m}_{bs}(h_{11} - h_{12s})\eta_{T-2} = \dot{m}_{ts}(h_4 - h_5)$	[35]
Consumption power of booster pump	$W_{P-1} = \dot{m}_{ts}(h_2 - h_1)$ $W_{P-2} = \dot{m}_{bs}(h_8 - h_7)$	[35]
Heat exchangers	$\dot{Q} = \dot{M}_c(h_{c,out} - h_{c,in}) = \dot{M}_c(h_{h,in} - h_{h,out})$	[35]
Total Thermal efficiency, η_{en}	$\eta_{en} = \frac{W_{T-1} + W_{T-2} + W_{T-3} - W_{P-1} - W_{P-2} - W_{P-3}}{h_{E1} - h_{E11}}$	-
Total exergy efficiency, η_{ex}	$\eta_{ex} = \frac{W_{T-1} + W_{T-2} + W_{T-3} - W_{P-1} - W_{P-2} - W_{P-3}}{E_{E1} - E_{E11}}$	-

$$\dot{E}_{E4} = \dot{E}_{E6} + \dot{Q}_{cond-3}\left(1 - \frac{T_o}{T_{cond-3}}\right) + \dot{E}_{d,\ c-3} \tag{28}$$

Applying Equations (17) and (23) gives the condenser exergy destruction rate as

$$\dot{E}_{d,T-3} = \dot{m}_{E4} T_o (s_{E5} - s_{E4}) + \frac{T_o}{T_{cond-3}} \dot{Q}_{cond-3} \tag{29}$$

Pump:

$$\dot{E}_{E5} + \dot{W}_{P-3} = \dot{E}_{E6} + \dot{E}_{d,\ P-3} \tag{30}$$

The net power output of these power plants is calculated as follows:

$$\dot{W}_{net,Geo} = \dot{W}_{T-3} - \dot{W}_{P_{-3}} \tag{31}$$

The energy and exergy efficiency are calculated as follows:

$$\eta_{en,geo} = \frac{\dot{W}_{net,geo}}{\dot{m}_{E1}\left(h_{E1} - h_{ref}\right)} \tag{32}$$

$$\eta_{ex,geo} = \frac{\dot{W}_{net,geo}}{\dot{E}_{E1} - \dot{E}_{E8}} \tag{33}$$

where h_{ref} is the geofluid specific enthalpy at ambient temperature (298.15 K) and pressure (1 bar).

$$T_{E7,opt} = \frac{T_{E1} + T_{E4}}{2} \tag{34}$$

Equation (34) shows that when the separator is operated at the average production well temperature and the condenser temperature, a single flash geothermal power plant provides the highest turbine power.

Assume that the system is near a steady-state to facilitate simulation. In addition, the isentropic efficiency of pumps and turbines has been achieved. The mathematical model of the proposed circulatory system is listed in Table 2.

Table 3 shows the expected parameters from the system simulation. For a given configuration, results can be achieved using these settings and the simulation model included in the Engineering Equation Solver (EES).

Table 4 shows the validation of the basic single flash geothermal cycle with the results of Assad et al. [36]. For single flash geothermal cycle validation, both of us and Assad et al., have used EES software. The equations used and the initial data are exactly the same as the information used by Assad et al. The software settings have been adjusted exactly according to the study of Assad et al. As a result, the results are exactly in accordance with the study of Assad et al. In the case of end-row differences, this is probably due to differences in the technique used in the geothermal cycle mixer.

Table 5 illustrates the properties of the various points of the system when R227ea and R116 are recovery working fluids in the two-stage ORC section.

Table 3
Data used to simulate the process.

Symbol	Value	Ref.
T_0 (Celsius)	25	–
P_0 (MPa)	0.101135	–
$T_{condGeo}$(Celsius)	50	[36]
η_{TGeo}	0.8	[36]
η_{T-1}	0.78	[35]
η_{T-2}	0.78	[35]
η_{PGeo}	0.8	[36]
η_{P-1}	0.8	[35]
η_{P-2}	0.8	[35]
ΔT_{DD}	5	[35]
m_{Geo} (kg/s)	50	[36]
m_{tc} (kg/s)	27	[35]
m_{bc} (kg/s)	25.2	[35]
T_{hotgeo} (Celsius)	300	[36]
P_{geo}(MPa)	1.5	[36]

Table 4
Validation by results comparison with MEH Assad et al. outputs.

state	Working Fluid	T(K)		P(MPa)		h(KJ/Kg)	
		Our results	Assad et al. [36]	Our Results	Assad et al. [36]	Our Results	Assad et al. [36]
E1	Geo Fluid	573.2	573.2	8.584	8.584	1344	1344
E2	Geo Fluid	448.2	448.2	0.8918	0.8918	1344	1344
E3	Geo Fluid	448.2	448.2	0.8918	0.8918	2773	2773
E4	Geo Fluid	323.1	323.1	0.01234	0.01234	2253	2253
E5	Geo Fluid	323.2	323.1	0.01234	0.01234	209.3	209.3
E6	Geo Fluid	323.3	323.3	1.5	1.5	211.2	211.2
E7	Geo Fluid	448.2	448.2	0.8918	0.8918	741.2	741.2
E8	Geo Fluid	411.9	439.9	0.3489	0.352	584	584

Table 5
Thermodynamic properties of states at $T_{E1} = 300^{o}\mathrm{C}$ and $T_{sep} = 175^{o}\mathrm{C}$.

State	T (K)	P(MPa)	h(kJ/kg)	s(kJ/kg.K)	$\dot{m}\left(\frac{kg}{s}\right)$	x	Exergy(kw)
1	256.6	0.1	1.753	0.006937	27	–	636.5
2	257.7	2.4	3.638	0.008414	27	–	675.5
3	365.1	2.4	139.3	0.4431	27	–	840.8
4	406.9	2.4	243.9	0.7217	27	–	1420
5	342.8	0.1	203.8	0.7554	27	–	65.86
6	256.6	0.1	82.84	0.3228	27	0.6151	283
7	194.7	0.1	−170.5	−1.106	25.2	–	1951
8	196.1	2.8	−168.4	−1.104	25.2	–	1988
9	265.6	2.8	−95.44	−0.788	25.2	–	1451
10	337.8	2.8	34.12	−0.3492	25.2	–	1419
11	376.2	2.8	71.56	−0.2437	25.2	–	1574
12	304.2	0.1	22.83	−0.1972	25.2	–	−3.874
13	201.1	0.1	−50.15	−0.4885	25.2	–	342.4
E1	573.2	8.584	1344	3.253	50	0	18931
E2	448.2	0.8918	1344	3.436	50	0.2967	16205
E3	448.2	0.8918	2773	6.625	14.83	1	11903
E4	323.1	0.01234	2253	7.028	14.83	0.858	2405
E5	323.2	0.01234	209.3	0.7037	14.83	0	60.28
E6	323.3	1.5	211.2	0.7049	14.83	–	83.04
E7	448.2	0.8918	741.2	2.091	35.17	0	4302
E8	411.9	0.3489	584	1.725	50	–	3687
E9	398.7	0.3489	527.5	1.584	50	–	2941
E10	381.4	0.3489	454.3	1.396	50	–	2078
E11	377	0.3489	435.4	1.347	50	–	1875

Table 6
Comparison of operating conditions of the basic cycle and the main proposed recovery cycle.

	Energy Efficiency	Exergy Efficiency	Net work(kw)	Input Heat(kJ)
Basic single Flash Geothermal cycle	0.2023	0.5044	7690	38003
Geothermal cycle with a two-stage ORC recovery	0.2178	0.5803	9898	45438

3. Results and discussion

3.1. Energy and exergy analysis

The findings of the sub-cycle of the same single flash geothermal cycle are compared with the findings of prior research to verify the existing system. The results are compared to those given by MEH. Assad et al. [36], indicating that the outputs are in good accord.

In order to continue the study, we must provide the necessary input parameters to calculate the mass, energy, and exergy equations. They are the temperature of the mass flow in mode 1, the temperature of the separator, the outlet pressure of the pump, the temperature or pressure of the condenser, and the isentropic efficiency of the steam turbine and the pump. Method 1 fluid temperature is 300 °C, well mass flow rate is 50 kg/s, steam turbine and pump isentropic efficiency is 0.85, pump outlet pressure is 1.5 MPa, and condenser temperature is 50 °C.

The impact of a two-stage ORC recovery cycle on the main system's performance was originally discussed. Table 6 shows the outcomes with and without the recovery cycle. According to the findings, adding recovery to the standard single flash cycle improves cycle efficiency. As shown in Table 6, the energy efficiency of the system has increased from 0.2023 to 0.2178, indicating that the first

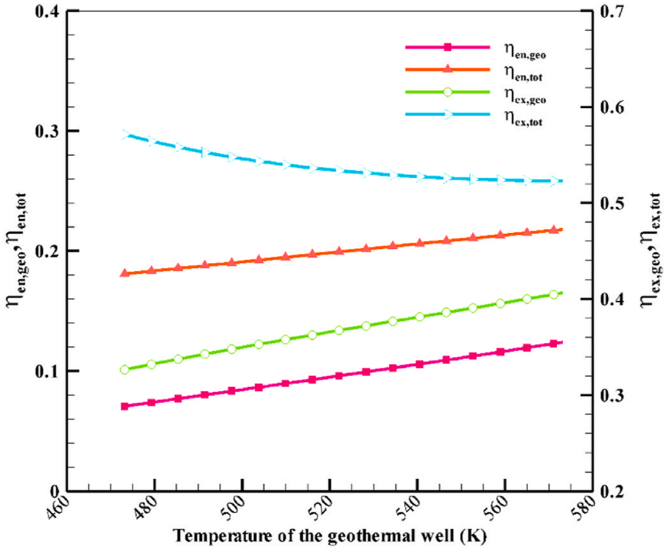

Fig. 3. Variation of energy and exergy efficiencies with the inlet temperature of the cycle in basic and recovery modes.

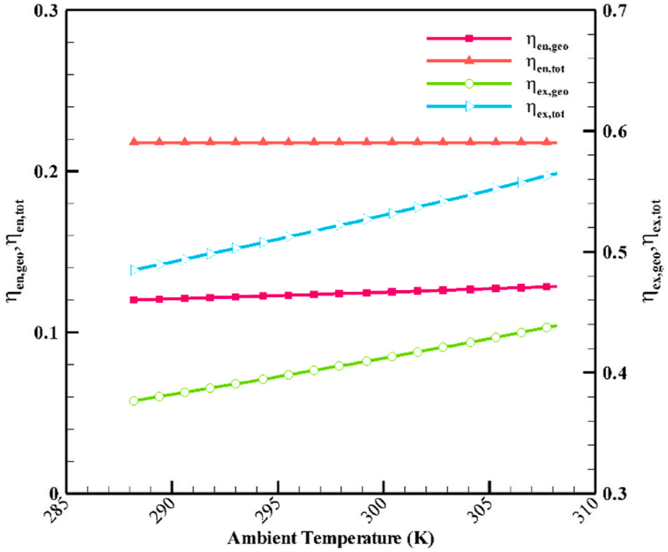

Fig. 4. Variation of energy and exergy efficiencies with the ambient temperature of the cycle in basic and recovery modes.

law efficiency of the system has increased by 7.5%. In the case of exergy efficiency, the value is increased from 0.5044 to 0.5803, which represents a 15% increase in the efficiency of the second law of system thermodynamics. Therefore, adding a recovery segment to the basic cycle will have a significant impact on the performance factors of the system.

Fig. 3 shows the effect of system inlet temperature changes on the energy efficiency and exergy efficiency of the single flash geothermal cycle and total recovery system. As the temperature increases from about 470 K to 570 K, not only the energy efficiency but also the exergy efficiency of the single flash geothermal cycle increases. Also, the energy efficiency of the total recovery system has an increasing trend, but the exergy efficiency of the total recovery system begins to decrease. In general, increasing the inlet temperature of the system from the geothermal well has a positive effect on the single flash geothermal cycle performance in terms of energy and exergy. But in the case of a total recovery cycle, we have to decide according to our goals.

Fig. 4 shows the effect of ambient temperature changes on the energy and exergy efficiencies of the single flash geothermal cycle and total recovery system. As the temperature increases from about 288 K to 308 K, the exergy efficiency of the single flash geothermal cycle and total recovery system increase. Also, the energy efficiency of single flash geothermal cycle is increasing very slowly, but the energy efficiency of the total recovery system is constant at 0.2778, It is not affected by changes in ambient temperature. It can be concluded that the proposed system is more efficient in warmer regions, as increasing the ambient temperature has a positive effect on the performance of the system.

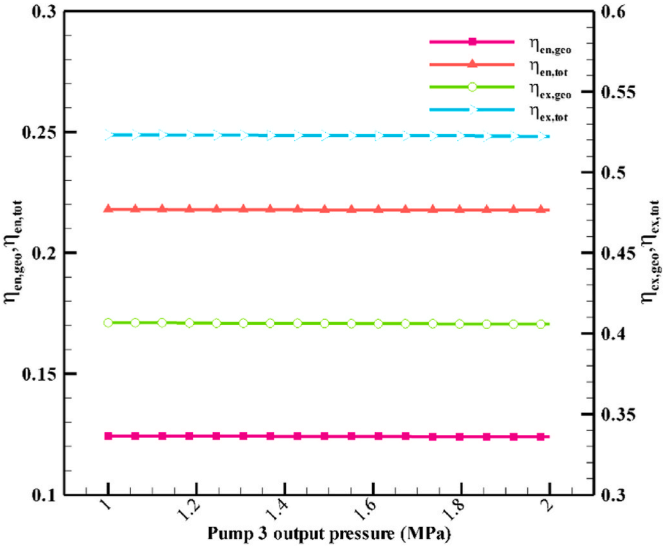

Fig. 5. Variation of energy and exergy efficiencies with geothermal turbine inlet pressure in the basic and the recovery modes.

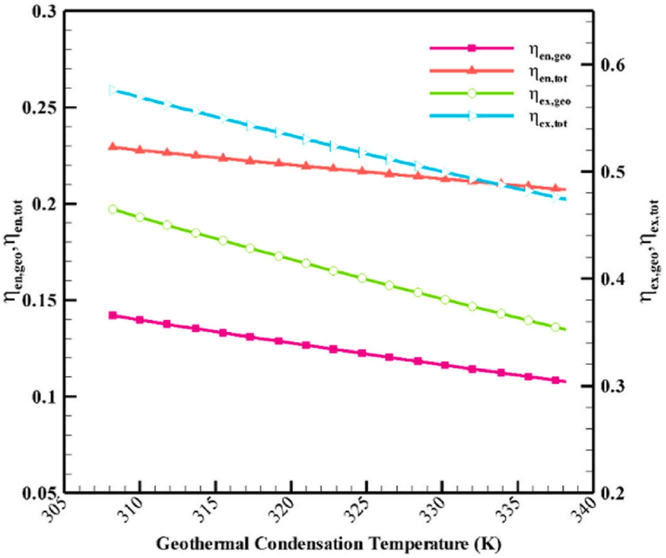

Fig. 6. Variation of energy and exergy efficiencies with the geothermal condensation temperature of the cycle in basic and recovery modes.

Fig. 5 represents the effect of pressure changes of pump 3 (single flash geothermal cycle pump) on energy efficiency and exergy efficiency of the single flash geothermal cycle and total recovery system. By increasing the pressure from 1 MPa to 2 MPa, all the studied parameters have a lightly decreasing trend. It can be concluded that increasing the pressure of pump 3 will have a negative effect on system performance, although the amount of changes is very small and negligible.

Fig. 6 shows the effect of changes in geothermal condensation temperature on the energy and exergy efficiencies of the system in both of the working modes. All the studied parameters decrease with a relatively steep slope as the condensation temperature increases from 308 K to 338 K. It can be concluded that increasing the condensation temperature of the geothermal cycle condenser has a negative effect on the operating parameters of the system in both operating modes.

Proposed two-stage organic Rankine cycle recover the single flash geothermal power plant exhaust heat. In general, by adding the recovery section to the basic single flash geothermal cycle, we see a significant increase in system design parameters. The thermal efficiency of the system will increase by 7.66% and the exergy efficiency of the system will increase by 15.04%. In addition, the total net work of the system will increase from 7690 kW to 9898 kW by a significant increase of 28.71%.

Table 7
Capital investment cost functions of various components.

$$\dot{C}_{tot} = \dot{C}_{fuel} + \sum_{k} \dot{Z}_{CI} + \dot{Z}_{O\&M} \tag{35}$$

$$\dot{Z}_{CI,k} + \dot{Z}_{O\&M,k} = \frac{\dot{Z}_k * \varphi}{N*3600} CRF \tag{36}$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{37}$$

Components	Cost functions	Ref.
Turbine	$4405*\dot{W}_T{}^{0.89}$	[37]
Pump	$1120*\dot{W}_p{}^{0.8}$	[37]
Condenser	$1397*A_{CD}{}^{0.89}$	[37]
Heat Exchanger	$1397*A_{HE}{}^{0.514}$	[37]
Expansion valve	$114.5*\dot{m}$	[38]
Separator	$280.3*\dot{m}_E{}^{0.67}$	[39]
Mixer	0	[40]

For the thermo-economic analysis, we have [37].

Table 8
Parameters used in the economic analysis.

Parameter	Value	Ref.
Annual operational hours the system, t	7300 h	[37]
Annual interest rate, i	14%	[37]
Life time of the system, n	15 years	[37]
Maintenance factor, φ	1.06	[37]

Table 9
Levelized energy cost (*LEC*) for both of the working modes.

	Basic single flash geothermal cycle	Total recovery system
LEC ($/kw)	0.125	0.108

3.2. Economic analysis

The mathematical formulae required to perform the economic analysis of the power plants are presented in this part. Tables 7 and 8 illustrate the capital investments made as well as the economic criteria used for each plant component. As shown in Table 7, the cost function of power components like turbines and pumps is a function of the components' performance, but the cost function of heat exchangers is a function of the exchanger's surface area.which $\dot{C}_{tot}$ is the total cost rate, $\dot{C}_{fuel}$ is the fuel cost rate, $\dot{Z}_{CI}$ is the cost rate of capital investment and $\dot{Z}_{O\&M}$ is the cost rate of operation and maintenance. In addition, $\dot{Z}_k$ is the cost rate of the capital investment for component k, N is the number of hours in a year, φ is the maintenance factor and CRF is the capital recovery factor. Furthermore, i is the annual interest rate and n is the power plant lifetime.

As an important economic parameter, the levelized energy cost (*LEC*) is stated as [41],

$$LEC = \frac{CRF*\ C_{tot} + C_{om}}{W_{net}\ t_{op}} \tag{38}$$

That $\dot{W}_{net}$ is the net power output of the power plant, C_{om} is the operation and maintenance cost, where is assumed to be 1.5% of $\dot{C}_{tot}$ and t_{op} is the annual operation time, that is assumed to be 7300 h.

As shown in Table 9, in the proposed recovery system, the cycle has less *LEC* than the basic single flash geothermal cycle. *LEC*. Reduced from 0.125 $/kw to 0.108 $/kw that shows a improvement from the economical point of view.

4. Conclusions

This paper presents energy, exergy and economic analysis of a two-stage ORC recovery cycle powered by a single flash geothermal power plant. The performance of the basic single flash geothermal power plants and the total recovery system were compared in terms of power generation, energy efficiency, exergy efficiency and economic parameters. A two-stage Organic Rankine Cycle (ORC) was created to recover heat losses in a single flash geothermal power plants at low temperatures. R227ea and R116 were used as working fluids for the top cycle and bottom recovery cycle, respectively. To determine their impact on cycle performance, several changes to the operating parameters at their optimal value were made. In comparison to a basic single flash geothermal power plant, a recovery power plant has better efficiency and power. The maximum output power (total net work) and maximum exergy efficiency of the two-stage ORC recovery system were 9898 kW and 58.03%, respectively. We can summarize the results of the present work as follows:

- According to the results, with adding of the recovery section to the basic cycle, the thermal efficiency increases from 0.2023 to 0.2178, which indicates a 7.66% improvement in this important parameter. Also, the exergy efficiency increases from 0.55044 to 0.5803, which also represents a 15.04% improvement from the exergy point of view. Furthermore, the total power output of the system increases from 7690 kW to 9898 kW, that shows a 28.71% considerable increase.
- From economical point of view, the cycle in the proposed recovery system has a lower LEC than a single flash geothermal cycle. LEC Reduced from 0.125 $/kw to 0.108 $/kw, which is an improvement in terms of cost.
- An increase in temperature at the entry to the system from a geothermal well has a positive effect on the energy and exergy characteristics of the basic flash geothermal cycle. But for a total recovery system, we must make a decision that is consistent with our goals. In addition, it can be concluded that the system proposes more efficiently in warmer areas because the increase in ambient temperature has a positive effect on system performance.

In conclusion, it can be stated that the output total power, energy efficiency and exergy efficiency of a recovery single flash geothermal power plant are always higher than a basic single flash geothermal power plant. For future research, researchers can study the current recovery cycle on a geothermal binary cycle. Also use seawater as a cooling source for the condenser cooling process. Using a variety of working fluids for the recovery ORC section to find the best possible options can also be used in future research.

CRediT authorship contribution statement

Guangli Fan: Resources, Formal analysis. **Yingjie Gao:** Methodology, Writing – review & editing. **Hamdi Ayed:** Resources, Formal analysis. **Riadh Marzouki:** Methodology. **Yashar Aryanfar:** Writing – original draft, Coding, Investigation, Conceptualization. **Fahd Jarad:** Writing – review & editing, Formal analysis. **Peixi Guo:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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