HYDROGEN, FUEL CELL & ENERGY STORAGE

Energetic and Exergetic Analysis of a Geothermal Energy System for Multigeneration Applications: A Thermodynamic Perspective

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Abstract

Recent research has increasingly focused on high-efficiency systems powered by renewable energy sources to address global warming, prevent ozone layer depletion, and ensure stable and accessible energy supplies. Among these sources, geothermal energy stands out for its ability to power thermodynamic systems capable of generating multiple outputs. The efficiency of a stand-alone flash-binary geothermal power plant decreases due to input energy losses. To enhance overall performance and reduce costs, structural modifications and waste heat recovery techniques can be implemented. This study proposes and investigates an innovative waste heat recovery system integrated into a dual-flash binary geothermal power plant. The combined system incorporates a Rankine cycle and a proton exchange membrane electrolyzer. The system focuses on two major processes: converting waste heat into power and producing hydrogen from the generated power. Its feasibility is evaluated from thermodynamic and economic perspectives. The system analysis was performed using EES (Engineering Equation Solver) software. Results indicate energy and exergy efficiencies of 23.97% and 35.35%, respectively. Moreover, the total power generated by the system, incorporating two turbines and two thermoelectric generators (TEGs), is 5981 kW. The system also produces hydrogen at a rate of 0.0295 kg/s. Moreover, based on the exergy destruction analysis, TEG 2 and the compressor exhibit the highest rates of exergy destruction.

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1 Introduction

Conversion of energy is crucial for satisfying human and industrial requirements when hot, chilling when cold, generating electricity (in numerous ways), and operating many mechanical systems. The selection of energy sources must be made very carefully and efficient technical solutions must be utilized to meet these requirements. In this regard, much effort has been placed to improve the energy utilization by merging different thermodynamic cycles through well-designed topologies to build multiple conversion systems [1]. The hybrid and multigeneration systems have been intensively investigated by researchers recently to improve the efficiency and effectiveness of energy systems. Such systems can lead to a considerable increase of the overall energy consumption compared to conventional single-purpose power generation technologies. Their primary function is to simultaneously produce two or more types of useful energy or energy-based products from a single energy source [2]. Thus, a considerable amount of research work has been given to the integration of renewable energy sources, especially geothermal energy, by employing advanced thermodynamic cycles for the construction of sustainable and efficient multigeneration systems.

Cao et al. [3] investigated the effect of various working fluids on the performance of a novel geothermal-driven multigeneration system. The proposed configuration consisted of a flash-binary geothermal power plant, an organic flash cycle (OFC), a combined power and cooling subsystem with an organic Rankine cycle (ORC) and a thermoelectric generator, a compression refrigeration cycle and hydrogen and freshwater production units. The manufacturing units were based on a humidification-dehumidification desalination system and a low-temperature electrolyzer. The results show that R123/R1234ze(e) is the best mixture in terms of overall energy efficiency, cooling capacity, hydrogen production rate and freshwater generation. Li et al. [4] proposed a novel Organic Flash Rankine Cycle (OFRC) integrated with an ejector (E-OFRC) for geothermal heat use. In this configuration the high-pressure throttle valve is replaced with an ejector to allow the first flash evaporation and a low-pressure throttle valve is used to flash separated the saturated liquid for the second time. The results of the optimization indicated a net output power of 84.75 kW, a specific investment cost of $2,833.54 /kW, and an annual reduction of CO_2-eq emissions of 0.807×10^6 kg, proving the technical and environmental benefits of the system.

Cui and Aziz [5] investigated the potential of geothermal energy for hydrogen production, emphasizing the restrictions of fossil fuel and growing significance of renewable energy sources. Their investigation demonstrated that the system might reach an energy efficiency of around 15% for dry steam sources above 200 °C. The wet steam regime is in a totally liquid condition. It allows to recover more than 10% of the geothermal fluid energy through the use of a mix of organic Rankine cycle technology and flash cycles. The levelized cost of hydrogen (LCOH) for dry steam production was determined to be 1.26 USD/kg which is more inexpensive than hydrogen production from natural gas, but, hybrid flash systems using liquid wet geofluid generated a minimum LCOH of 5.23 USD/kg.

Zare and Rostamnejad [6] proposed a new combined cooling, heating, and power (CCHP) system based on geothermal energy. The system is a combination of a Rankine cycle and an ejector transcritical refrigeration cycle. The results show that the addition of an internal heat exchanger considerably improves the system performance with gains of 30.9%, 49.1% and 75.8% in exergy output, net power generation and cooling capacity respectively. Wang et al. [7] highlighted the importance of combined cooling and power systems to increase the overall efficiency of power plants and the possibility of Organic Rankine Cycle (ORC) and ejector refrigeration cycle (ERC) technologies for the exploitation of medium-temperature geothermal energy. They proposed a combined cooling and power (CCP) system based on geothermal flash, ORC and ERC technologies. The results indicated an overall thermal efficiency of 18.16% and an exergy efficiency of 59.16%. The ejector cooling cycle was characterized by a coefficient of performance (COP) of 0.1224 with a cooling capacity of 93.73 kW.

A novel multistage facility using geothermal energy was suggested by Yilmaz et al. [8]. The system comprises a transcritical Rankine cycle, a proton exchange membrane (PEM) electrolyzer, a multi-effect desalination (MED) unit and an ejector cooling system (ECS). The simulation findings indicate that the proposed plant can generate a net power output of 982.4 kW and hydrogen at a rate of 0.0024 kg/s. The total energy and exergy efficiencies were obtained as 40.04% and 36.31%, respectively. Hsieh et al. [9] developed a geothermal reservoir model by connecting the flash-binary cycle model in MATLAB with the thermo-hydro-mechanical (THM) approach in COMSOL Multiphysics. The integrated model was used to evaluate the system performance combining thermodynamic, heat transport, and economic evaluations. The results reveal that the output power decreases by 52.08% over the first 30 years of operation as the flash pressure increases, and the first- and second-law efficiencies decline by 34.53% and 24.53%, respectively.

A multigeneration system based on geothermal energy for simultaneous power, cooling and hydrogen synthesis was proposed by Chen et al. [10]. The proposed configuration is a geothermal power plant with a customized transcritical CO_2 cycle for the production of power and cooling, and a water electrolyzer for hydrogen production. Thermodynamic, economic and exergoenvironmental simulations showed that the system can produce around 991.40 kW net power, 71.77 kW cooling capacity and 2.51 kg/h of hydrogen with a total exergy efficiency of 34.90%. Onat et al. [11] completed a technoeconomic optimization and feasibility study on a geothermal heat pump system for sustainable heating and energy uses. The system is composed of an organic Rankine cycle coupled with district heating and a heat pump assisted greenhouse heating unit, based on real operational data of a 120 °C low temperature geothermal source. The optimized trigeneration system achieved an overall energy efficiency of 64.98% and an exergy efficiency of 75.94%, producing 2.86 MW of electricity and 19.71 MW of useable heat output simultaneously. The heat pump subsystem reached a coefficient of performance (COP) of 4.519, and the economic evaluation indicated energy expenses of 0.03548 kWh and district heating costs of 0.03396 kWh, with a payback period of 2.688 years

Mirshafiee et al. [12] studied the energy and exergy performance of a hybrid multigeneration system for production of electricity, freshwater and hydrogen using geothermal water and solar energy. The system consists of a photovoltaic/thermal unit, an organic rankine cycle, an alkaline electrolyzer and a reverse osmosis desalination unit. The ORC is thermally powered by the geothermal water at 154 °C and can create roughly 671 kW of power for the hydrogen production. The system provides an overall exergy efficiency of 43% with about 1.397 kg/s of fresh water production rate and 18.5 kg/h of hydrogen generation rate. The total capital cost was estimated at 1.98 million dollars and the payback period was roughly four years.

Khazaei Nam et al. [13] built and optimized a geothermal-driven multigeneration system by complete energy, exergy, exergoeconomic and exergoenvironmental (4E) study. Abstract A combined Kalina cycle, double-effect absorption chiller and vapor compression refrigeration system for simultaneous production of power, cooling, hot water and potable water is proposed. Under base operating conditions, the system provides 63.45 kW net electricity, 80.91 kW cooling load, 329.1 kW hot water and 20.82 L/h potable water. The optimization results revealed a 6.83% and 1.8% gain in energy and exergy efficiency respectively. The estimated payback period was roughly 6.5 years.

Yilmaz et al. [14] performed a parametric evaluation of a multigeneration system relying on geothermal energy for the concurrent production of electricity, hydrogen, ammonia, freshwater and heating. The envisaged facility comprises a geothermal cycle, two organic Rankine cycles based on ammonia, a PEM electrolyzer, an ammonia synthesis unit and a reverse osmosis desalination system. The results demonstrate that the system is capable of producing 2046 kW of net power, while producing 0.002367 kg/s of hydrogen and 0.009436 kg/s of ammonia. The total energy and exergy efficiencies were found to be 26.31% and 33.09%, respectively.

A considerable amount of research has been done on geothermal-based multigeneration systems, integrating different thermodynamic cycles for the production of electricity, cooling, hydrogen, fresh water and other goods. The existing researches are mostly focused on improving the system efficiency using the cycle integration, working fluid selection or multi-objective optimization. Innovative adjustments to standard components in these systems for further improvement of power generation performance have gotten scant attention. Specifically, the potential application of thermoelectric generators (TEGs) as a substitute for conventional condenser units in geothermal flash-binary plants has not been addressed in the previous work.

Therefore, the present work proposed and analyzed a geothermal flash-binary system with two thermoelectric generators to replace traditional condensers for the purpose of recovering more waste heat and improving power generation. The thermodynamic performance of the proposed configuration is investigated to evaluate its potential to enhance the overall system efficiency and power output compared to traditional geothermal power systems.

2 System Modeling and Descriptions

Figure 1 illustrates a system that harnesses geothermal energy to generate power, cooling, and hydrogen. This is achieved through the integration of binary flash cycles, organic flash cycles combined with condensation refrigeration, and a proton exchange membrane (PEM) electrolyzer. Geothermal fluid is initially obtained as a high-pressure saturated liquid at state 1. After passing through expansion valve 1 at state 2, its pressure is reduced before entering the flash tank. In the flash tank, saturated steam is generated at state 3 and subsequently used to drive the turbine, producing electricity. After exiting the turbine at state 4, the fluid passes through TEG unit 1 at state 5, before being pumped before being reinjected into the wells at state 6.

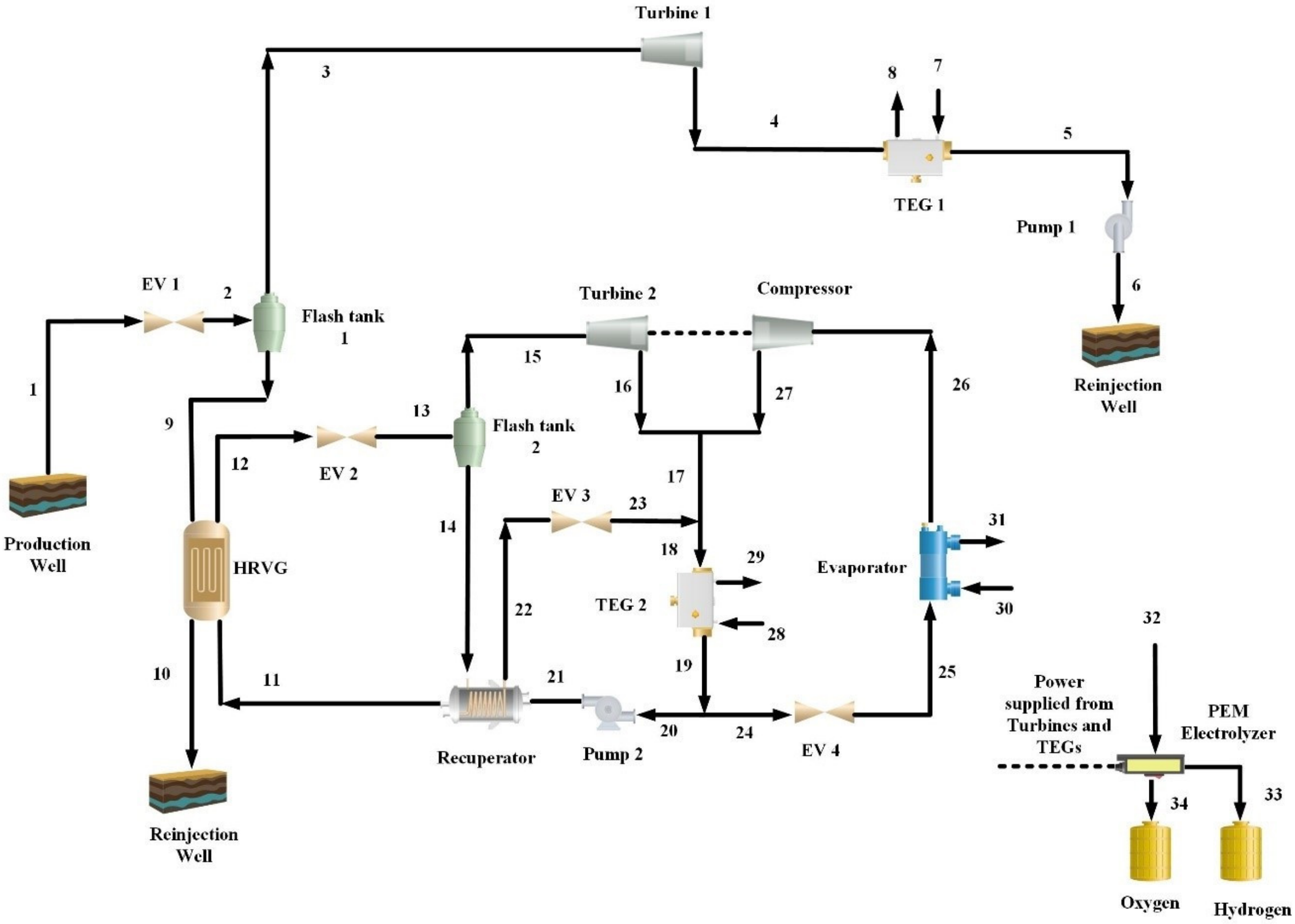

Fig. 1. The diagram of the studied system

The saturated liquid leaving flash tank 1 at state 9 holds adequate energy to drive the organic flash cycle. After heat exchange, the fluid is reinjected into the ground at state 10. Following heat absorption at state 12, the working fluid is directed to expansion valve 2, where its pressure is reduced at state 13 before entering flash tank 2. The turbine generates power by receiving saturated steam from flash tank 2 at state 15. The recuperator receives the saturated liquid from flash tank 2 at state 14, removes heat at state 22, and then the liquid enters expansion valve 3, where its pressure decreases. In the compression refrigeration cycle, the working fluid absorbs heat in the evaporator, transforming into a saturated vapor state at state 26. The compressor condenses the saturated steam exiting the evaporator at state 27, which then mixes with the steam from turbine 2. The resulting mixture at state 17 is combined with the steam from expansion valve 3. The working fluid at state 18 enters TEG unit 2. The output of the TEG unit at state 19 is split into two flows: one directed to the evaporator at state 24 and the other to the pump at state 20. The flow to the evaporator passes through throttling valve 4, reducing its pressure at state 25. The flow to the pump enters a recuperator after being pressurized at state 21. After heat absorption, the working fluid at state 11 enters a heat recovery steam generator. The energy generated by the turbines and TEG units is used to meet the power requirements of the PEM electrolyzer for hydrogen production.

The system has been subjected to a comprehensive thermodynamic analysis, which includes the examination of mass balance equations, energy balance equations, governing equations for exergy output, exergy degradation, and an economic analysis. Based on the current conditions and cycle, the following assumptions are made:

- Heat transfer to the surroundings and pressure drops in the pipes are neglected.
- The system is assumed to operate in a steady-state condition.
- Constant enthalpy is assumed for the process oc-

curring within the expansion valve.

- The output from the evaporator and condensers is assumed to be saturated.
- Kinetic and potential energy changes are omitted in the thermodynamic equations.
- Chemical exergy analysis is excluded from the exergy equations.
- Isentropic efficiency is used in the design of turbines, pumps, and compressors. The heat and power transfer, along with the exergy degradation rate for each component, can be calculated using the energy and exergy balance equations defined for the proposed multigeneration system, as presented in Table 1.

Table 1. The proposed system equations for energy balance and exergy destruction rate for each equipment

Equipment	Energy balance equations	Exergy destruction rate equations
Compressor	$\dot{W}_{\mathrm{comp}} = \dot{m}_{26}(h_{27} - h_{26})$	$\dot{E}x_{D,\mathrm{comp}} = \dot{W}_{\mathrm{comp}} + \dot{E}x_{26} - \dot{E}x_{27}$
Turbine 1	$\dot{W}_{T1} = \dot{m}_3(h_3 - h_4)$	$\dot{E}x_{D,T1} = \dot{E}x_3 - \dot{W}_{T1} - \dot{E}x_4$
Turbine 2	$\dot{W}_{T2} = \dot{m}_{15}(h_{15} - h_{16})$	$\dot{E}x_{D,T2} = \dot{E}x_{15} - \dot{W}_{T2} - \dot{E}x_{16}$
HRVG	$\dot{Q}_{\mathrm{HRVG}} = \dot{m}_9(h_9 - h_{10}) = \dot{m}_{11}(h_{12} - h_{11})$	$\dot{E}x_{D,\mathrm{HRVG}} = \dot{E}x_9 + \dot{E}x_{11} - \dot{E}x_{10} - \dot{E}x_{12}$
Recuperator	$\dot{Q}_{\mathrm{REC}} = \dot{m}_{14}(h_{22} - h_{14}) = \dot{m}_{11}(h_{11} - h_{21})$	$\dot{E}x_{D,\mathrm{REC}} = \dot{E}x_{14} + \dot{E}x_{21} - \dot{E}x_{22} - \dot{E}x_{11}$
Evaporator	$\dot{Q}_{\mathrm{eva}} = \dot{m}_{25}(h_{25} - h_{26}) = \dot{m}_{30}(h_{31} - h_{30})$	$\dot{E}x_{D,\mathrm{eva}} = \dot{E}x_{2}5 + \dot{E}x_{30} - \dot{E}x_{26} - \dot{E}x_{31}$
Flash Tank 1	$\dot{Q}_{\mathrm{FT1}} = \dot{m}_2(h_2 - h_3 - h_9)$	$\dot{E}x_{D,\mathrm{FT1}} = \dot{E}x_2 - \dot{E}x_3 - \dot{E}x_4$
Flash Tank 2	$\dot{Q}_{\mathrm{FT2}} = \dot{m}_{13}(h_{13} - h_{14} - h_{15})$	$\dot{E}x_{D,\mathrm{FT2}} = \dot{E}x_{13} - \dot{E}x_{14} - \dot{E}x_{15}$
Pump 1	$\dot{W}_{p1} = \dot{m}_5(h_6 - h_5)$	$\dot{E}x_{D,p1} = \dot{W}_{p1} - \dot{E}x_5 + \dot{E}x_6$
Pump 2	$\dot{W}_{p2} = \dot{m}_{20}(h_{21} - h_{20})$	$\dot{E}x_{D,p2} = \dot{W}_{p2} - \dot{E}x_{20} + \dot{E}x_{21}$
TEG 1	$\dot{Q}_{\mathrm{TEG1}} = \dot{m}_4(h_4 - h_5) = \dot{m}_7(h_8 - h_7)$	$\dot{E}x_{D,\mathrm{TEG1}} = \dot{E}x_7 + \dot{E}x_7 - \dot{E}x_5 - \dot{E}x_8$
TEG 2	$\dot{Q}_{\mathrm{TEG2}} = \dot{m}_{18}(h_{18} - h_{19}) = \dot{m}_{28}(h_{29} - h_{28})$	$\dot{E}x_{D,\mathrm{TEG2}} = \dot{E}x_{18} + \dot{E}x_{28} - \dot{E}x_{19} - \dot{E}x_{29}$
PEM	$\dot{W}_{\mathrm{PEM}} = (\dot{m}_{32}h_{32} - \dot{m}_{33}h_{33} - \dot{m}_{34}h_{34})$	$\dot{E}x_{D,\mathrm{PEM}} = \dot{E}x_{32} + \dot{W}_{\mathrm{PEM}} - \dot{E}x_{33} - \dot{E}x_{34}$

3 Results and Discussion

Simulating the multigeneration system involves selecting specific parameters. Table 2 lists the input parameters required for system modeling, which must be defined prior to conducting further calculations.

The system simulation conducted using EES [15] software reveals an energy efficiency of 23.97% and an exergy efficiency of 35.35%. Additionally, the cycle generates 5981 kW of power. Replacing the condensers with a TEG unit has the potential to generate an additional 1978.5 kW of power. Under the primary assumptions, this multigeneration system is capable of producing 0.0295 kg/s of hydrogen. Figure 2 illustrates the effect of increasing the initial flash tank temperature on the energy and exergy performance of the cycle. The graphs show that raising the temperature of the first flash tank enhances the energy efficiency from 8.83% to 25.19% and improves the exergy efficiency from 9.66% to 37.17%.

Figure 3 illustrates the impact of adjusting the second flash tank temperature on the power production of the two TEG units. The results show that increasing the second flash tank temperature from 380 K to 410 K reduces the power output of TEG 2 from 3395 kW to 2687 kW, while the power output of TEG 1 remains constant at 178.5 kW. This constancy in TEG 1's power output occurs because changes in the second flash tank temperature do not affect TEG 1 or the upper section of the system but significantly influence TEG 2's performance.

Table 2. Input parameters for cycle analysis

Parameters	Unit	Value
Geothermal energy		
Geothermal water temperature	°C	200
Geothermal water pressure	kPa	1000
Flash tank		
Flash tank 1 pressure	kPa	300
Flash tank 2 pressure	kPa	835
Evaporator temperature	°C	5
PEM		
P_{H_2}, P_{O_2}	(atm)	1
T_{PEM}	°C	80
$E_{\mathrm{act},a}$	kJ/mol	76
$E_{\mathrm{act},c}$	kJ/mol	18
λ_a	-	14
λ_c	-	10
D	mm	50
J_a^{ref}	A/m^2	1.7×10^5
J_c^{ref}	A/m^2	4.6×10^3

Figure 4 illustrates the effect of the geothermal water mass flow rate on the system's energy and exergy efficiencies. The graphs show that as the mass flow rate increases from 10 kg/s to 18 kg/s, both the energy and exergy efficiencies decline. Specifically, the energy efficiency decreases from 51.75% to 13.7%, while the exergy efficiency drops from 76.33% to 20.2%.

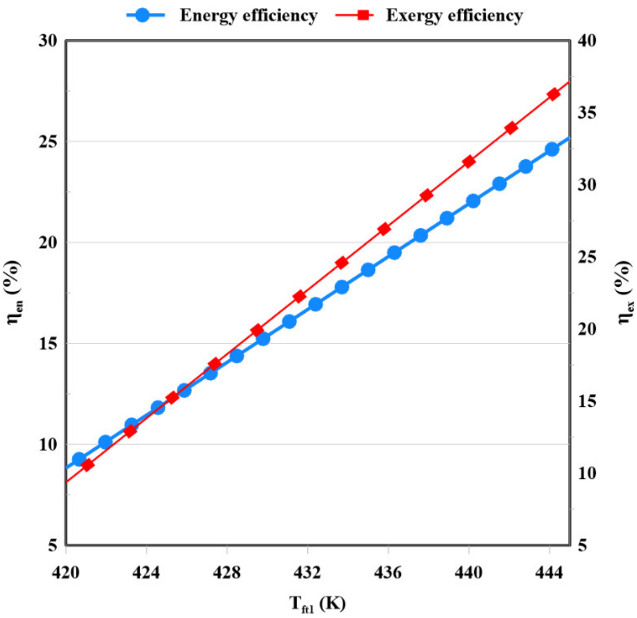

Fig. 2. The impression of the first flash tank on the energy and exergy efficiency of the system

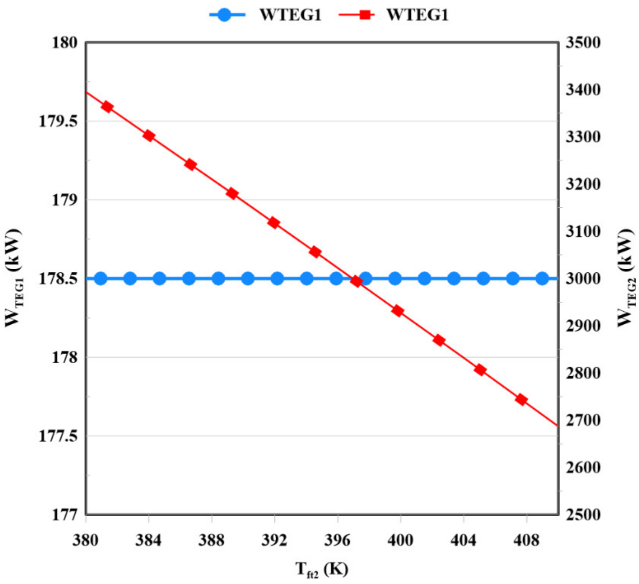

Fig. 3. The impression of the second flash tank on the total power production by the TEG units

Figure 5 shows the effect of the temperature difference on the efficiency of the heat recovery steam generator. The graphs show that as the temperature difference increases, the system's energy output improves, but its exergy output decreases. Specifically, a change in temperature difference from 5 to 12 results in a 10.2% increase in energy efficiency and a 16.2% decrease in exergy efficiency. The system's energy output rises from 21.07% to 23.38%, while its exergy output declines from 41.46% to 34.74%.

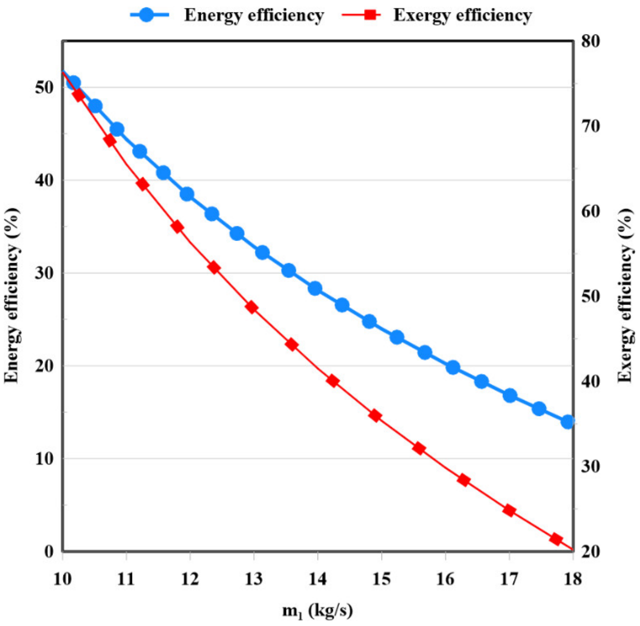

Fig. 4. The effect of the geothermal mass flow rate on the energy and exergy efficiency of the system

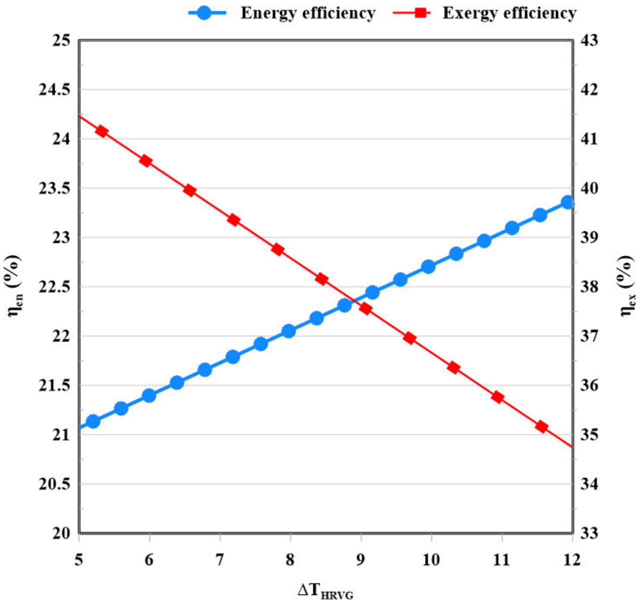

Fig. 5. The impression of the temperature difference of the heat recovery vapor generator on the efficiency of the system

Figure 6 clarifies the relationship between the total power production rate and the heat generated in the evaporator. The graphs indicate that as the temperature difference increases, the system's power production decreases, while the heat generated in the evaporator rises. Specifically, when the temperature difference increases from 5 to 12, the system's power generation drops from 4737.6 kW to 4124.4 kW, while the heat production rate increases from 531 kW to 678 kW. This indicates that by increasing the temperature difference by 140%, the power production rate decreases by 12.9%, while the heat generated by the system increases by 27.6%.

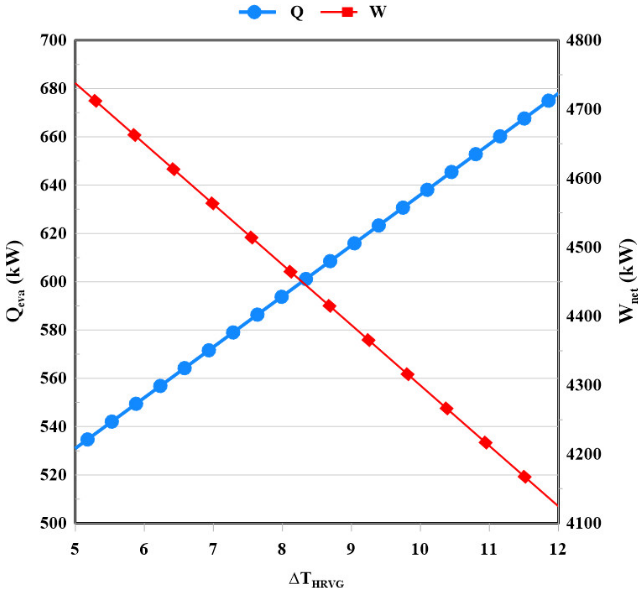

Fig. 6. The influence of the temperature difference of the heat recovery vapor generator on the amount of power and heat of the system

The ZT value, which serves as the performance indicator, directly impacts the efficiency of the thermoelectric units. As shown in Figure 7, an increase in this parameter leads to higher energy and exergy efficiencies for the system. A higher ZT value enhances power generation by the two TEG units, resulting in an overall increase in the system's power output, which, in turn, improves the system's efficiency. Specifically, changing the figure of merit from 0.3 to 1 leads to an increase in energy output from 23.09% to 23.97% and an improvement in exergy efficiency from 34.06% to 35.35%.

Figure 8 illustrates the impact of the figure of merit (ZT) on the power output of the two TEG units. The figure of merit directly influences the power generated by the TEGs. As a result, an increase in ZT leads to a higher power output from both TEGs. The findings show that as ZT increases from 0.3 to 1, the power output of TEG1 increases from 136.7 kW to 178.5 kW. Similarly, the power output of TEG2 rises from 1632 kW to 1809 kW as ZT increases.

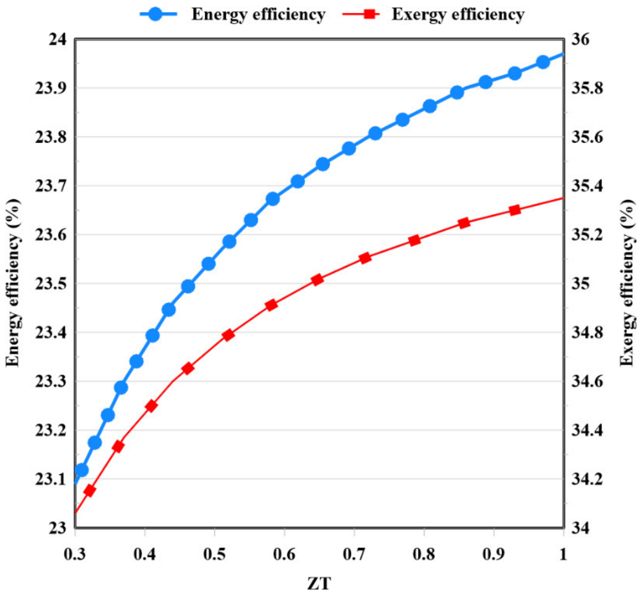

Fig. 7. The effect of the ZT on the energy and exergy efficiency of the system

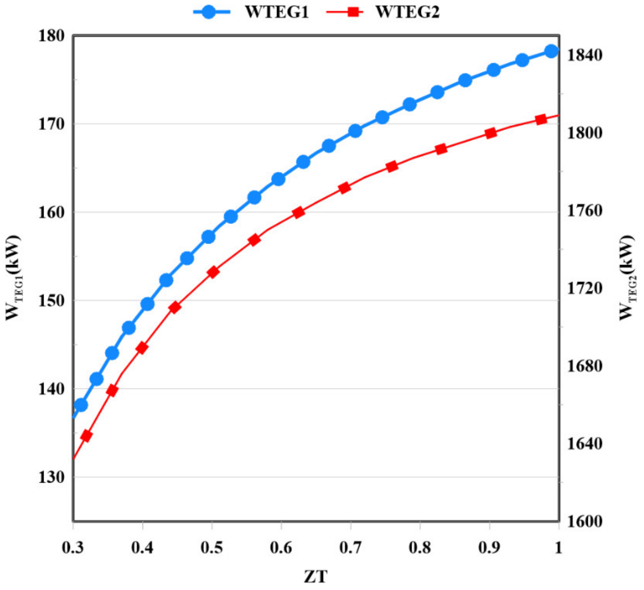

Fig. 8. The effect of the ZT on the amount of power produced by the TEGs

4 Conclusion

The thermodynamic assessment was conducted to evaluate the performance of the proposed geothermal energy-based cycle for power generation, refrigeration, and hydrogen production, utilizing a binary flash cycle and a PEM electrolyzer. This cycle combines a basic condensation refrigeration cycle with a binary flash cycle, with geothermal energy acting as the primary energy source. The simulation was carried out using

EES software, and a parametric study was performed to assess the feasibility of the proposed cycle under various input conditions. The results indicate that the system demonstrates energy and exergy outputs of 23.97% and 35.35%, respectively. The total power output generated by the system, which includes two turbines and two thermoelectric generators (TEGs), is 5981 kW. Additionally, the system can produce 0.0295 kilograms of hydrogen per second. Improved energy and exergy efficiencies are achieved by increasing the temperature of the first flash tank. Increasing the temperature of the second flash tank has no impact on the power generation rate of TEG1 but leads to a reduction in the power output of TEG2. As the geothermal mass flow rate increases, both the energy and exergy efficiencies of the system decrease. Elevating the temperature difference increases energy efficiency and heat production in the evaporator, but this also results in a reduction of exergy efficiency and power production rates. On the other hand, an increase in the figure of merit (ZT) leads to enhanced energy and exergy efficiencies, as well as improved power generation rates.

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