

Hydrogen Production Potential of a System Powered by Geothermal Energy and Thermoelectric Generators

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Abstract

This study presents a thermodynamic analysis of a power, refrigeration, and hydrogen production cycle utilizing geothermal energy in a binary flash cycle. The system combines a basic vapor-compression refrigeration cycle with a binary flash cycle and a PEM electrolyzer, with geothermal energy serving as the driving force. A thorough thermodynamic simulation was carried out using EES software, followed by a parametric study of the proposed cycle to evaluate its performance under varying input parameters. The results indicate that TEG 2 and the compressor exhibit the highest exergy destruction rates, as revealed by the exergy degradation rate analysis. Furthermore, increasing the temperature of the first flash tank leads to higher hydrogen and power production rates. In contrast, raising the temperature of the second flash tank results in decreased energy and exergy efficiency, as well as lower power and hydrogen generation rates. Additionally, an increase in the geothermal mass flow rate leads to a reduction in both power and hydrogen production. Finally, it is observed that a larger temperature difference causes a decrease in the hydrogen generation rate.

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1 Introduction

The use of clean and renewable energy sources has become increasingly critical due to the depletion of fossil fuels, the limited availability of non-renewable resources, and their detrimental environmental impact, all of which threaten the sustainability of human life. Energy plays a crucial role in the progress and advancement of nations, with experts emphasizing the efficient utilization of available energy resources as a key driver of economic and industrial development, alongside human power. Energy sources are typically categorized into nuclear energy, fossil fuels (such as oil, gas, and coal), and renewable energy (including solar, geothermal, wind, and biomass). The growing importance of electrical energy in economic development and societal progress is undeniable. Recent research has established a direct correlation between a country's level of development and its electricity consumption, highlighting the need for simultaneous growth in both areas [1,2].

With the increasing demand for energy and the decline in fossil fuel usage, alongside concerns about nuclear energy and environmental issues, significant efforts have been made to transition to renewable sources, including geothermal energy. Geothermal energy, which is derived from the heat generated by molten masses of radioactive materials deep within the Earth, is a renewable energy source. Many researchers have explored the application of geothermal energy in various systems. Yousefi et al. [3] conducted modeling, analysis, and comparison of four different systems for harnessing geothermal energy. They found that the efficiency of a dual-flash tank power plant surpasses that of a single-flash tank by 36.3%. Finally, the electricity and heat production from this system resulted in a reduction of 696,200 tons of carbon dioxide emissions compared to power plants relying on fossil fuels. In their study, Zheng et al. [4] introduced a novel Combined Heat and Power system utilizing a Kalina cycle and a compression heat pump cycle to simultaneously supply electricity and hot air to consumers. Upon analyzing the exergy losses of the system under initial design operation conditions, it was found that the steam generator and heat supplier were responsible for significant exergy destruction in the equipment. Subsequently, a thermodynamic parametric analysis was conducted, revealing an optimal high pressure for maximizing the system's exergy efficiency. Interestingly, it was known that the turbine inlet temperature had minimal effect on the exergy efficiency of the system.

Mosaffa and Zareei [5] suggested an Improved Organic Flash Cycle that incorporates an internal heat exchanger to enhance thermal energy recovery from a

flash tank. Their findings indicate that the net power output increases by 36.7% when a two-phase expander is used instead of a flash tank under the specified conditions. Additionally, the net power output experiences a 1.2% increase when two separate flashing stages are employed in the EOFC subsystem. Abdolalipouradl et al. [6] investigated and performed a thermodynamic analysis on four different binary flash systems: a single flash tank, two flash tanks of type 1, two flash tanks of type 2, and three flash tanks. Their findings revealed that the binary flash system with two flash tanks of type 1 generates 4.03% more power compared to the system with a single flash tank, 1.32% more power than the system with two flash tanks of type 2, and 1.2% more power than the system with three flash tanks. Pan and Farkoush [7] conducted a study on a double-flash binary system that integrates an organic Rankine cycle and an ejector refrigeration cycle for waste heat recovery. Their research showed that Pentane-Isohexane demonstrated excellent performance, generating a net power output of 1.9 MW and a cooling load of 290.15 kW. This resulted in a total exergetic efficiency of 58.33% and a payback period of 6.70 years. In a separate study, Pratama and Koike [8] utilized thermodynamic modeling to identify the most suitable power generation system based on power output, energy, and exergy performance. The results revealed that the flash-binary cycle achieved the highest power output, with a 21% increase over the single-flash cycle at a 5 °C pinch point, and a 7% increase over the double-flash cycle.

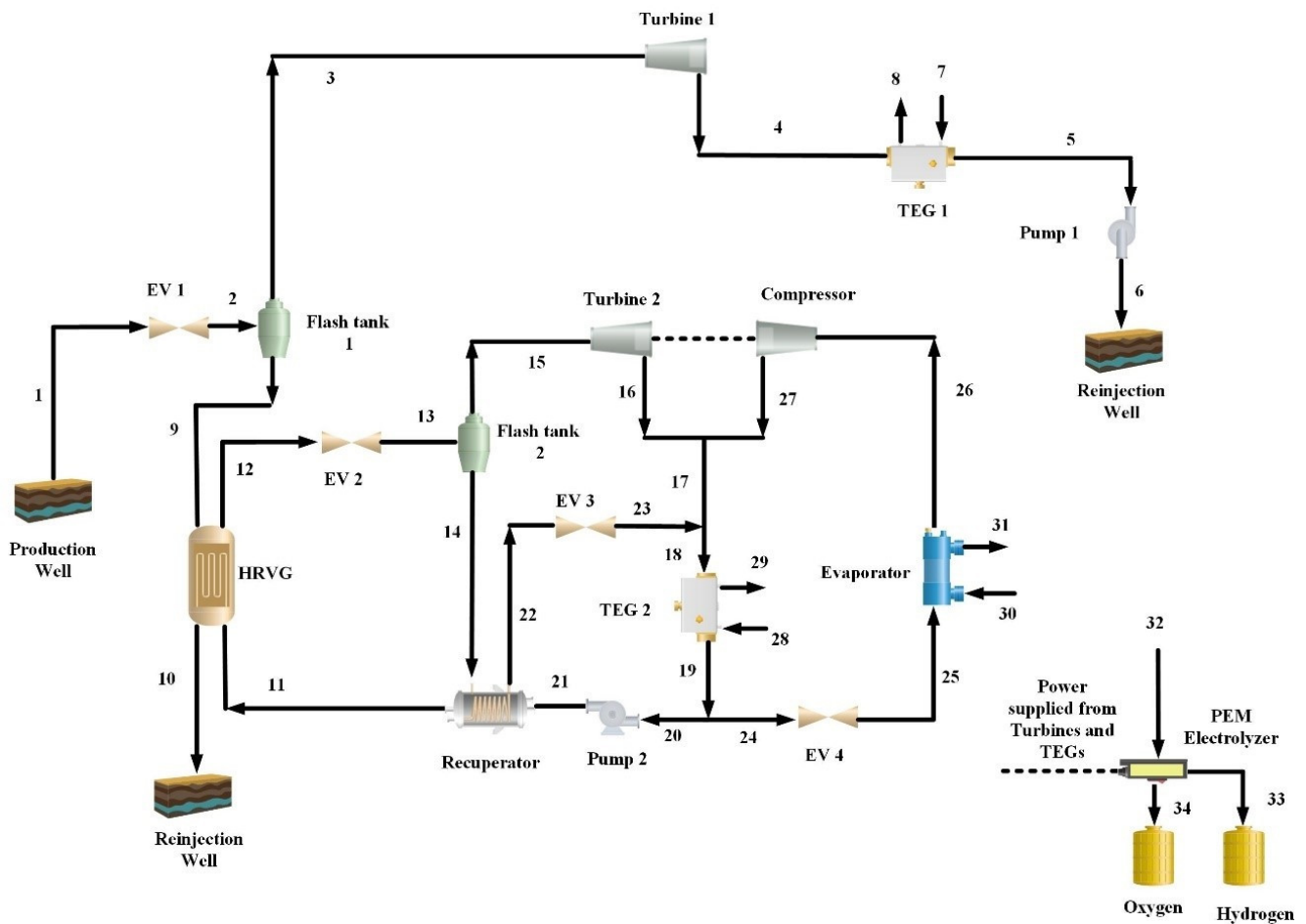
2 System Modeling

The diagram in Figure 1 illustrates a system that combines generation of power, cooling, and hydrogen using geothermal energy. It utilizes binary flash cycles and integrates organic flash cycles with condensation refrigeration, along with a PEM electrolyzer for hydrogen production.

- The geothermal fluid is initially extracted as a high-pressure saturated liquid (state 1). The pressure of the fluid is then reduced as it passes through expansion valve 1 (state 2) and flows into the flash tank. In the flash tank, saturated steam is produced (state 3), which is then used to drive the turbine and generate power. The fluid exiting the turbine (state 4) passes through TEG unit 1 (state 5) and is then pumped before being reinjected into the wells (state 6). The saturated liquid leaving flash tank 1 (state 9) contains sufficient energy to drive the organic flash cycle, and after heat exchange, it is reinjected into the ground (state 10). Following heat absorption

(state 12), the working fluid is directed to expansion valve 2, where its pressure is reduced (state 13) before entering flash tank 2. The turbine generates power as it receives the 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. The pressure of the working fluid decreases in expansion valve 3. In the compression refrigeration cycle, the working fluid turns into a saturated vapor state at state 26 after absorbing heat in the evaporator. The compressor condenses the saturated vapor coming out of the evaporator at state 27, and it mixes with the steam from turbine 2. The resulting mixture at state 17 is then combined with the steam from expansion valve 3. The working fluid at state 18 enters TEG unit 2. The output from the TEG unit at state 19 is split into two flows: one is 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, which reduces its pressure at state 25. The flow to the pump enters a recuperator after being pressurized at state 21. Following heat absorption, the working fluid at state 11 enters the heat recovery steam generator. The energy generated by the turbines and TEG units is then used to meet the power requirements of the PEM electrolyzer for hydrogen production. The mass balance equations, energy balance equations, governing equations for exergy efficiency, exergy degradation, and the economic analysis of the system have all been thoroughly examined through thermodynamic analysis. Based on the current conditions and the cycle configuration, the following assumptions are made: The transfer of heat to the environment and the pressure change in the pipes have been neglected.



- The operating condition of the system is considered as steady state.
- The process inside the expansion valve is enthalpy constant.
- Evaporator output and condensers are assumed to be saturated.
- The analysis of kinetic and potential energy changes in thermodynamic equations is omitted.
- Chemical exergy analysis is omitted in exergy

equations.

- Isentropic efficiency has been used to design turbines, pumps and compressors.

The energy and exergy balance relations for the referred multigeneration system can be utilized to calculate the heat and power transferred, as well as the exergy degradation rate of each equipment, as outlined in [Table 1](#).

Table 1. Equations of energy balance and exergy destruction rate for each equipment

Equipment	Energy balance equations	Exergy destruction rate equations
Compressor	$\dot{W}_{\text{comp}} = \dot{m}_{26}(h_{27} - h_{26})$	$\dot{E}_{X,D,\text{comp}} = \dot{W}_{\text{comp}} + \dot{E}_{X26} - \dot{E}_{X27}$
Turbine 1	$\dot{W}_{T1} = \dot{m}_3(h_3 - h_4)$	$\dot{E}_{X,D,T1} = \dot{E}_{X3} - \dot{W}_{T1} - \dot{E}_{X4}$
Turbine 2	$\dot{W}_{T2} = \dot{m}_{15}(h_{15} - h_{16})$	$\dot{E}_{X,D,T2} = \dot{E}_{X15} - \dot{W}_{T2} - \dot{E}_{X16}$
HRVG	$\dot{Q}_{\text{HRVG}} = \dot{m}_9(h_9 - h_{10}) = \dot{m}_{11}(h_{12} - h_{11})$	$\dot{E}_{X,D,\text{HRVG}} = \dot{E}_{X9} + \dot{E}_{X11} - \dot{E}_{X10} - \dot{E}_{X12}$
Recuperator	$\dot{Q}_{\text{REC}} = \dot{m}_{14}(h_{22} - h_{14}) = \dot{m}_{11}(h_{11} - h_{21})$	$\dot{E}_{X,D,\text{REC}} = \dot{E}_{X14} + \dot{E}_{X21} - \dot{E}_{X22} - \dot{E}_{X11}$
Evaporator	$\dot{Q}_{\text{eva}} = \dot{m}_{25}(h_{25} - h_{26}) = \dot{m}_{30}(h_{31} - h_{30})$	$\dot{E}_{X,D,\text{eva}} = \dot{E}_{X25} + \dot{E}_{X30} - \dot{E}_{X26} - \dot{E}_{X31}$
Flash Tank 1	$\dot{Q}_{\text{FT1}} = \dot{m}_2(h_2 - h_3 - h_9)$	$\dot{E}_{X,D,\text{FT1}} = \dot{E}_{X2} - \dot{E}_{X3} - \dot{E}_{X4}$
Flash Tank 2	$\dot{Q}_{\text{FT2}} = \dot{m}_{13}(h_{13} - h_{14} - h_{15})$	$\dot{E}_{X,D,\text{FT2}} = \dot{E}_{X13} - \dot{E}_{X14} - \dot{E}_{X15}$
Pump 1	$\dot{W}_{p1} = \dot{m}_5(h_6 - h_5)$	$\dot{E}_{X,D,p1} = \dot{W}_{p1} - \dot{E}_{X5} + \dot{E}_{X6}$
Pump 2	$\dot{W}_p = \dot{m}_{20}(h_{21} - h_{20})$	$\dot{E}_{X,D,p2} = \dot{W}_{p2} - \dot{E}_{X20} + \dot{E}_{X21}$
TEG 1	$\dot{Q}_{\text{TEG1}} = \dot{m}_4(h_4 - h_5) = \dot{m}_7(h_8 - h_7)$	$\dot{E}_{X,D,\text{TEG1}} = \dot{E}_{X7} + \dot{E}_{X7} - \dot{E}_{X5} - \dot{E}_{X8}$
TEG 2	$\dot{Q}_{\text{TEG2}} = \dot{m}_{18}(h_{18} - h_{19}) = \dot{m}_{28}(h_{29} - h_{28})$	$\dot{E}_{X,D,\text{TEG2}} = \dot{E}_{X18} + \dot{E}_{X28} - \dot{E}_{X19} - \dot{E}_{X29}$
PEM	$\dot{W}_{\text{PEM}} = (\dot{m}_{32}h_{32} - \dot{m}_{33}h_{33} - \dot{m}_{34}h_{34})$	$\dot{E}_{X,D,\text{PEM}} = \dot{E}_{X32} + \dot{W}_{\text{PEM}} - \dot{E}_{X33} - \dot{E}_{X34}$

3 Results and Discussion

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		
$P_{\text{H}_2}, P_{\text{O}_2}$	atm	1
T_{PEM}	°C	80
$E_{\text{act},a}$	kJ/mol	76
$E_{\text{act},c}$	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

The input data required for simulating the multigeneration system involves selecting specific parameters. [Table 2](#) lists the input parameters for system modeling. Defining these parameters is essential for performing the subsequent calculations.

Using the EES software, an analysis of the system was conducted to compare and outline the operational characteristics of the proposed multigeneration system, as presented in [Table 3](#).

Table 3. The general simulation results for the proposed system

Parameters	Unit	Value
η_{en}	%	23.97
η_{ex}	%	35.35
$\dot{W}_{T1}$	kW	157.5
$\dot{W}_{T2}$	kW	3836
$\dot{W}_{\text{TEG1}}$	kW	178.5
$\dot{W}_{\text{TEG2}}$	kW	1809
$\dot{W}_{\text{net}}$	kW	5981
$\dot{m}_{\text{H}_2}$	kg/s	0.0295
$\dot{E}_{X,d,\text{tot}}$	kW	35722

Exergy degradation is a key method for improving the system's output. This section analyzes the exergy losses in the cycle equipment. Figure 2 illustrates the exergy destruction rates of the main system components. The highest exergy loss rates are observed in TEG 2, the compressor, and the turbines. Exergy destruction is particularly significant in equipment where

a temperature difference exists between two streams. In TEG 2, the temperature difference leads to the highest exergy degradation rate. Exergy is lost in irreversible processes, and in the TEG, the exergy loss is higher due to significant pressure drops and heat transfer to the environment, compared to other components of the system.

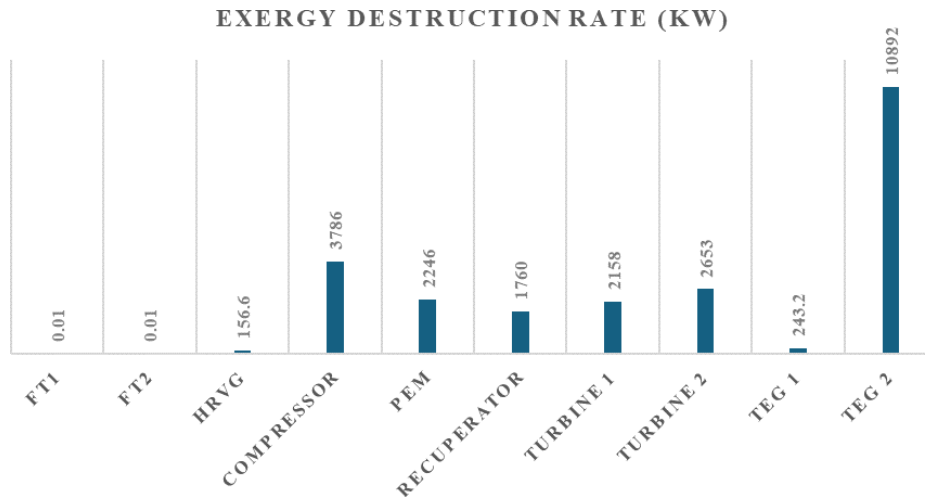


Fig. 2. Exergy loss rate in the equipment used in the cycle

The results shown in Figure 3 illustrate the effect of the initial flash tank temperature on both total power production and hydrogen generation rate. The findings clearly indicate that increasing the first flash tank temperature from 420 K to 445 K results in an upward trend in both power and hydrogen generation rates. As the flash tank temperature rises, the system's power output increases from 318.4 kW to 6288 kW, while the hydrogen generation rate rises from 0.001572 kg/s to 0.03105 kg/s. The energy required for the PEM electrolyzer is provided by the turbines and TEG units within the system under study. Consequently, as the system's power output increases, the hydrogen generation rate also increases. The increase in the second flash tank's temperature has no effect on the first turbine, resulting in constant power production from the first turbine. However, the temperature rise does impact the lower part of the system, leading to a reduction in fluid quality from the second pressure relief valve and a decrease in the flow rate to the second turbine. Furthermore, the temperature increase in the tank raises the inlet temperature of the second turbine. This rise in temperature also elevates the process fluid temperature toward the recovery converter, resulting in a higher outlet temperature from the converter. According to the first law of thermodynamics, the increase in temperature at the recovery converter outlet directly im-

pacts the fluid flow to the lower system, specifically toward the evaporator and compressor. This leads to an increase in cooling production and higher power consumption by the compressor.

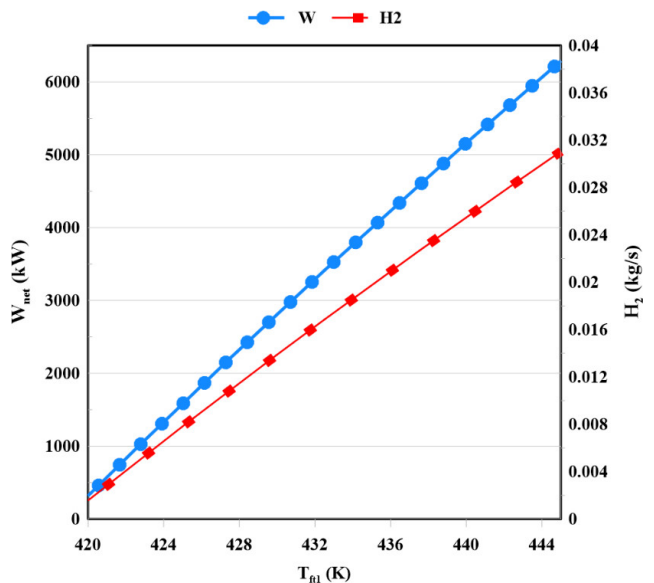


Fig. 3. The impression of the first flash tank on the total power production and the hydrogen production rate of the system

The impact of the second flash tank temperature on the thermal and exergetic performance of the system is shown in Figure 4. It is clear that as the temperature of the second flash tank increases, both efficiencies experience a significant decrease. Specifically, when the flash tank temperature increases from 380 K to 410 K, the energy efficiency drops from 32.12% to 28.42%, and the exergy efficiency decreases from 47.37% to 41.92%.

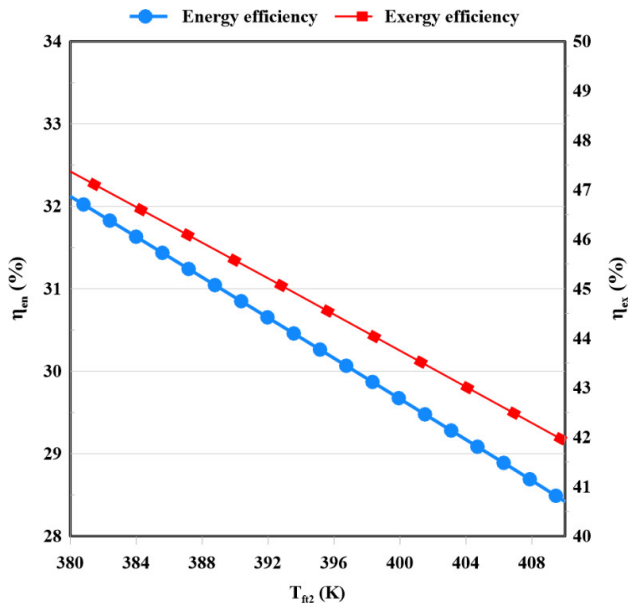


Fig. 4. The effect of the second flash tank on the energy and exergy efficiency of the system

Figure 5 illustrates the effect of the second flash tank temperature on both total power generation and the rate of hydrogen production. The results show a significant decrease in both power and hydrogen generation rates as the temperature of the second flash tank increases from 380 K to 410 K. As the flash tank temperature rises, the system's power output decreases from 8015 kW to 7093 kW, while the hydrogen production rate decreases from 0.03957 kg/s to 0.03502 kg/s. It is important to note that hydrogen production is directly linked to the system's power generation. Therefore, as the power output decreases, the hydrogen production rate also decreases.

Figure 6 illustrates the changes in both the total power production rate and hydrogen generation rates. The graphs indicate that an increase in the geothermal mass flow rate negatively affects both the total power production and hydrogen production rates. Specifically, when the mass flow rate of geothermal water rises from 10 kg/s to 18 kg/s, the system's power production decreases from 8610 kW to 4102 kW. Similarly, the hydrogen production rate decreases from 0.04251 kg/s to 0.02026 kg/s.

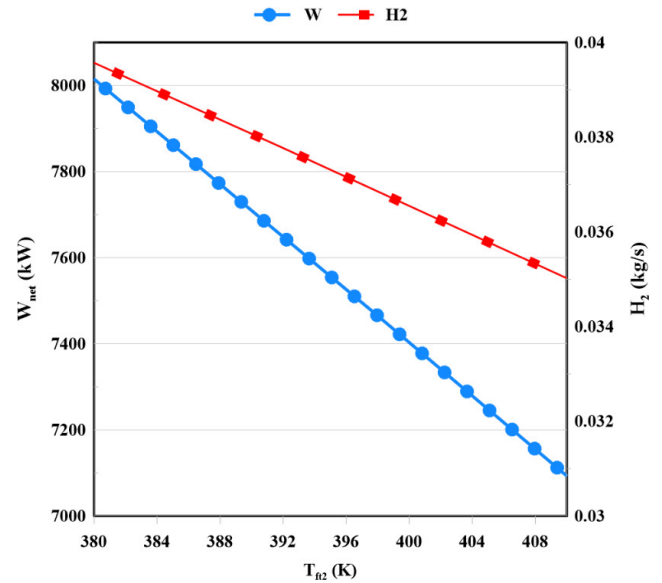


Fig. 5. The impact of the second flash tank on the total power production and the hydrogen production rate of the system

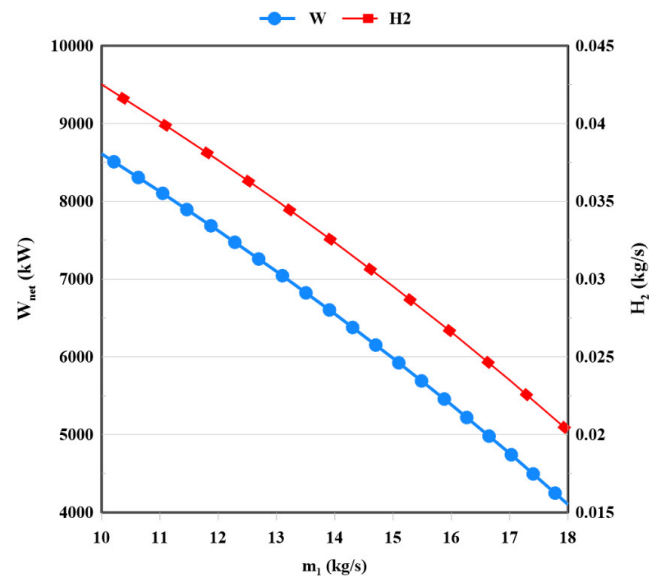


Fig. 6. The impact of the geothermal mass flow rate on the total power production and the hydrogen production rate of the system

Figure 7 shows the relationship between the hydrogen generation rate and the temperature difference in the HVRG. The data indicates that as the temperature difference increases, the system's hydrogen production decreases from 0.02339 kg/s to 0.02037 kg/s. The reduction in hydrogen production rate is ascribed to the decline in the total power generation rate as the temperature difference increases.

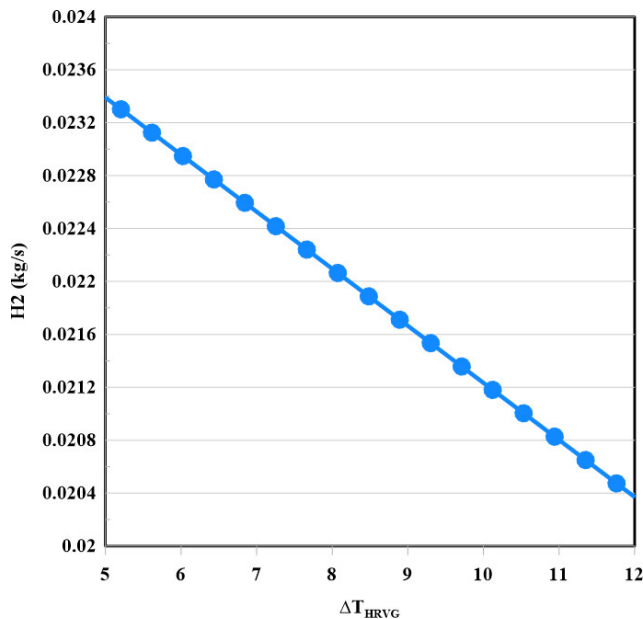


Fig. 7. The impression of the temperature difference of the heat recovery vapor generator on the amount of hydrogen production of the system

4 Conclusion

- The proficiency of the proposed cycle for power generation, refrigeration, and hydrogen production using geothermal energy in a binary flash cycle has been evaluated from a thermodynamic perspective. The proposed cycle combines a simple condensation refrigeration cycle with a binary flash cycle and a PEM electrolyzer, with geothermal energy serving as the driving source. The major outputs of the system are hydrogen, power, and cooling. In this research, thermodynamic analysis was employed as an effective tool to evaluate the cycle's performance. A comprehensive thermodynamic simulation was conducted using EES software, followed by a parametric study of the proposed cycle to assess its operability under the given input parameters. The key findings from this study are as follows: The first law and the second law outcomes of the system are 23.97% and 35.35%, respectively.
- The total quantity of power generated by the system which is the combination of two turbines and two TEGs is 5981 kW.
- This system produces 0.0295 kg/s hydrogen.
- According to the exergy destruction rate, TEG 2

and compressor have the maximum amounts of exergy destruction rates.

- By increasing the first flash tank temperature, power and hydrogen generation rate of the system increases.
- By augmenting the second flash tank temperature, energy and exergy efficiencies, power and hydrogen generation rate of the system decreases.
- By augmenting the geothermal mass flow rate, power and hydrogen generation rate of the system decreases.
- Because of the increasing temperature difference, the hydrogen production rate decreases.

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