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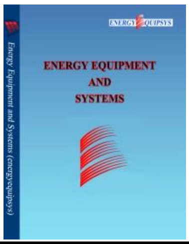

Enhanced performance and reduced payback period of a low grade geothermal-based ORC through employing two TEGs

Author

Ali Habibollahzade [a],
Ehsan Houshfar [a*]
Mehdi Ashjaee [a]
Ehsan Gholamian [a]
Amirmohammad Behzadi [a]

[a] School of Mechanical Engineering, College of Engineering, University of Tehran, P.O. Box 11155-4563, Tehran, Iran

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ABSTRACT

In this paper, a novel integrated system is proposed to improve the performance of a conventional low-grade geothermal-based organic Rankine cycle (ORC). The main idea is to utilize two TEG units to recover the waste heat of the condenser and geothermal brine. The proposed model is investigated and compared with simple ORC from the energy, exergy, and exergoeconomic viewpoints through the parametric study. Furthermore, the payback period of the systems is calculated to investigate the economic aspects of the model in more details. Results show that the exergy efficiency of the proposed system would be 56.81% at the base case (4.67% higher than the simple geothermal-based ORC system) and the total product cost of the proposed integrated system is 24.55 $/GJ at the base case (5.5% lower than simple ORC), while the payback period of the suggested system is 2.422 years (15 days lower than the simple ORC cycle). Furthermore, the net power output of the novel proposed system is 75.24 kW (9% higher than the simple ORC cycle). Comprehensive paramedic study and comparison of the exergy and exergoeconomic aspects reveal that the proposed system is a promising method to optimize such systems from exergy/exergoeconomic viewpoints.

Keywords: Exergy; Exergoeconomic; ORC; Geothermal; Thermoelectric Generator.

1. Introduction

The increasing demand of energy forces the researchers to explore the alternative (especially renewable-based) energy sources and design and optimize novel integrated co-generation systems and technologies. Among the major optimization approaches, maximizing the exergy efficiency and minimizing the product cost are widely considered in the literature for energy conversion systems. However, as these two objectives are conflicting each other for the majority of optimization problems in energy systems, it is generally required to approach the problem with a multi-objective optimization (MOO) method.

Recently, employing renewable-based co-generation power plants has become a hot topic as they can contribute towards the world energy policy targets such as sustainable and secure power supply. Among the renewables, geothermal is considered as a reliable and promising energy source. The organic Rankine cycles (ORCs) are introduced and adopted as favorite technologies for the sake of their configuration simplicity, components availability and better economics. Over the last two decades, a large number of studies have been devoted to analyze and optimize the

[*] Corresponding author: Ehsan Houshfar
School of Mechanical Engineering, College of Engineering, University of Tehran, P.O. Box 11155-4563, Tehran, Iran
Email: houshfar@ut.ac.ir

ORC-based systems by single and MOO methods. Braimakis and Karellas [1] investigated different ORC configurations with various working fluids from the energetic viewpoint. They reported relative efficiency gains, ranging from 4.98% to 9.29%, for recuperative configurations over the simple ORC. Yang *et al.* [2] used the genetic algorithm to optimize the ORC performance employed for a diesel engine waste heat recovery. They considered the net power output and exergy destruction rate as separate objective functions and reported a net output power of 13.84 kW at the optimal operating condition. Considering the exergy efficiency and specific cost of output power, single and MOO are performed for a novel ORC-based configuration for Sabalan geothermal power plant by Aali *et al.* [3], who also examined different ORC working fluids. They found R141b as the best working fluid and showed that, for single objective optimization, the specific cost of power is 4.901 $/GJ with an exergy efficiency of 52.56% for the plant, while the MOO leads to an exergy efficiency of 54.87% with a power cost of 5.068 $/GJ. Xi *et al.* [4] optimized the performance of three different ORC configurations with various working fluids using a genetic algorithm for low grade waste heat recovery considering the exergy efficiency as the single-objective function. Their results indicate that the double-stage regenerative system has the highest energy and exergy efficiencies and R141b is one of the recommended working fluids. The ORC performance for low temperature heat sources studied thermodynamically by Wang *et al.* [5], who implemented a genetic algorithm to conduct a single-optimization considering the net power output as the objective function. Considering isobutane as the working fluid, at the optimal operating condition, they reported a value of 49.88 kW for net power output and also showed that the best system performance can be achieved using isobutene as the ORC working fluid. To compare the performance of various ORC configurations for binary geothermal power plants, Zare [6] conducted an exergoeconomic analysis and single-objective optimization considering the total product cost as the objective. The study suggested that, from the thermodynamic point of view, the ORC with internal heat exchanger has superior performance, while from the economic viewpoint the basic ORC is the best case among the considered systems. The optimization results showed that the lowest total product cost and total capital investment and shortest payback period belongs to the basic ORC.

In recent years, integration of thermoelectric generators (TEGs) with conventional power generation systems is extensively investigated to improve the energy conversion efficiency. The integrated TEG systems are considered as an emerging technology because of many advantages such as the capability of direct heat to electricity conversion, no emissions, no chemical reaction, low operating and maintenance cost, and silent operation [7, 8]. Combining TEGs with other conventional power plants such as ORC-based systems are proposed and investigated in the literature recently [9–14]. Chávez-Urbiola *et al.* [10] analyzed solar-based systems integrated with TEG designed to operate at temperatures of 50–200 °C. Their reults indicated that the efficiency of TEG could reach 4% for the considerd operating conditions. Zare and Palideh [11] proposed the integration of TEG with a Kalina cycle driven by geothermal energy and indicated an enhancement of 7.3% for the net output power and energy and exergy efficiencies for the integrated system compared to the standalone Kalina cycle. Ziapour *et al.* [12] proposed an integration of ORC and TEG to enhance the power production from a solar pond power plant using two different models. In the first model, the condenser of the ORCis replaced with a TEG, while in the second model TEG is coupled to the ORC employing an intermediate heat exchanger. The results showed that for models 1 and 2, the thermal efficiency of the power plant can increase by 0.21% and 0.2% compared to the ORC without TEG which yields an efficiency of around 2.6%. Maraver and Royo [13] proposed and analyzed a simple plant layout consisting of a TEG and an existing biomass fueled ORC. They reported that the total exergy efficiency of the system can increase up to 8% by integeration with TEG system.

To the best of authors' knowledge, there is no research that is performed comprehensive energy, exergy and exergoeconomic analysis of a geothermal-based ORC integrated with TEG. In this study, a novel method is proposed to improve the performance of the system by implementing TEG units to recover the waste heats. Main novelties and objectives of this study can be summarized as follow:

- A novel geothermal based system is proposed by replacing the TEG units to recover the waste heat of the working fluid and geothermal brine.

- The systems are compared from energy, exergy, and exergoeconomic standpoints through a comprehensive parametric study.

The payback periods of the systems are presented.

Nomenclature

A	Area (m^2)
c	Specific cost ($/GJ)
$\dot{C}$	Cost rate ($/h)
E	Energy
$\dot{E}$	Exergy rate (kW)
F	Faraday constant
f	Exergoeconomic factor
h	Enthalpy
i_r	Interest rate
K	Conductivity
$\dot{m}$	Mass flowrate
n	Operating years
P	Pressure
$\dot{Q}$	Heat rate (kW)
R	Resistance
T	Temperature
ΔT^{LM}	Mean logarithmic temperature
$\dot{W}$	Power (kW)
Z	Investment cost
$\dot{Z}$	Investment cost rate
ZT_M	Figure of merit

Subscripts and superscripts

0	Dead state
1, 2, 3…	State number
CI	Capital investment
Cond	Condenser
C.V	Control volume
D	Destruction
ELEGA	Efficient liquid-based electricity
NT	generation apparatus
ev	Evaporator
F	Fuel
H	High
I	First law of thermodynamics
II	The second law of thermodynamics
in	inlet
L	Low
M	Mean
OM	Operating and maintenance
out	Outlet
p	Product
pu	Pump
SG	Steam generator
t	Turbine
TEG	Thermoelectric generator
tot	total

Abbreviations

CRF	Capital recovery factor
ORC	Organic Rankine cycle
PP	Payback period

Greek letters

η	Efficiency
τ	Annual operating hours

2. Systems description and assumptions

Schematic of the proposed system is illustrated in Fig.1, where the TEG units are used to recover the waste heat of the condenser and geothermal brine. As the figure depicts, in the proposed system, geothermal brine heats up the ORC working fluid by means of an evaporator and a superheater. The fluid then passes through the turbine at state 4 and thereafter is cooled down by passing on the TEG unit at state 5. Some portion of the waste heat can be converted to electricity using the TEG unit. Indeed, hot water passes on the hot side of the TEG and is cooled down with the water which is entered into the cold side of the TEG at state 6. The temperature difference between the hot and cold side of the TEG is the main driving force of the TEG power generation. Cooled down fluid is yet pumped again to the evaporator (states 1 and 2).

On the other hand, heat exchanged geothermal brine enters the second TEG unit and thus because of the temperature difference between the sides of the TEG, the unit generates power.

Following assumptions are made in this work to model the proposed system:

- The system operates at steady state condition.
- Potential and kinetic energy changes are omitted.
- Pressure drop inside the piping system is ignored.
- Pumps and the turbine are presumed as adiabatic equipment.

Saturated fluid is considered for the geothermal brine.

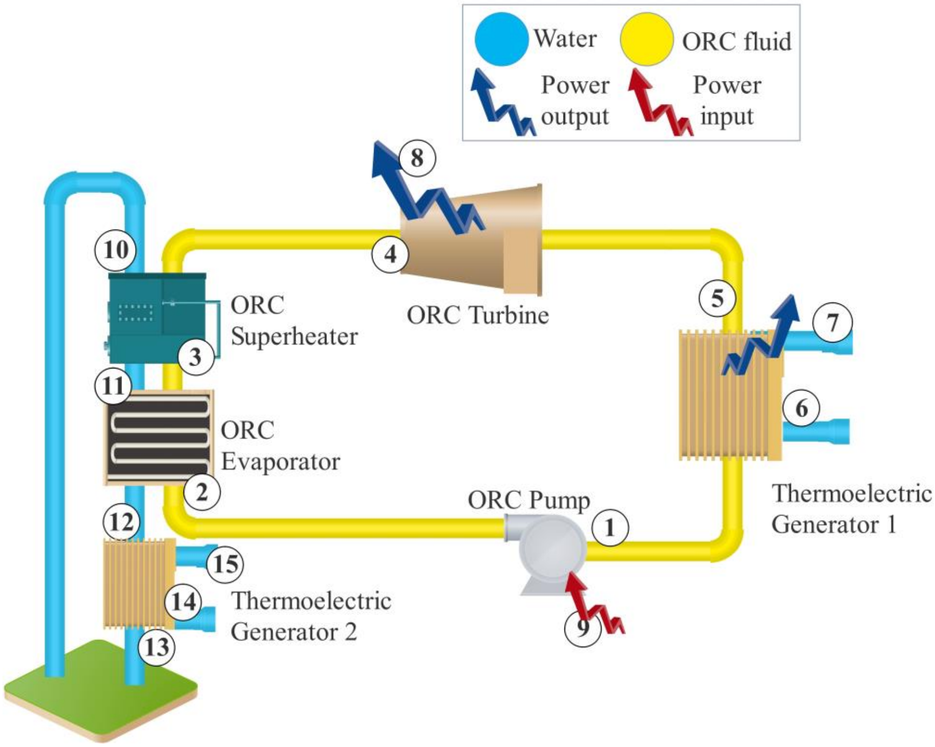


Fig. 1. Schematics of the proposed integrated energy system

3.Modeling

Thermodynamic analysis and simulation of the systems are performed by implementing Engineering Equation Solver (EES) software. Energy, exergy, and exergoeconomic analyses are carried out to make a comprehensive examination and performance comparison between the two proposed systems. For energy and exergy modeling of the systems, each component is assumed as a control volume for which the principles of the first and second law of thermodynamics are applied. Furthermore, the exergoeconomic analysis is performed using the specific exergy costing method (SPECO).

$$\dot{Q}_{C.V} - \dot{W}_{C.V} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \quad (1)$$

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} + \dot{E}_D \quad (2)$$

Energy balance equations, exergy destruction and exergy efficiency for each component of the system are listed in Table 1.

Table 1. Energy and exergy balances and exergy efficiency for each component of the three proposed model

Component	Energy balance	Exergy destruction rate	Exergy efficiency
Steam turbine	$\dot{W}_t=\dot{m}_5(h_4-h_5)$	$\dot{E}_{D,t}=\dot{E}_4-\dot{E}_5-\dot{W}_t$	$\eta_{II,t}= \dot{W}_t/(\dot{E}_4-\dot{E}_5)$
Pump	$\dot{W}_{pu}=\dot{m}_2(h_2-h_1)$	$\dot{E}_{D,pu}=\dot{E}_1-\dot{E}_2+\dot{W}_p$	$\eta_{II,pu}= (\dot{E}_2-\dot{E}_1)/\dot{W}_p$
Evaporator and superheater	$\dot{m}_{10}(h_{10}-h_{12})=\dot{m}_2(h_4-h_2)$	$\dot{E}_{D,ev}=(\dot{E}_{10}-\dot{E}_{12})-(\dot{E}_4-\dot{E}_2)$	$\eta_{II,ev}=(\dot{E}_4-\dot{E}_2)/(\dot{E}_{10}-\dot{E}_{12})$
Condenser	$\dot{m}_5h_5+\dot{m}_6h_6=\dot{m}_1h_1+\dot{m}_7h_7$	$\dot{E}_{D,cond}=\dot{E}_5-\dot{E}_1-(\dot{E}_7-\dot{E}_6)$	$\eta_{II,cond}=(\dot{E}_7-\dot{E}_6)/(\dot{E}_5-\dot{E}_1)$
TEG unit 1	$\dot{m}_5h_5+\dot{m}_6h_6=\dot{m}_1h_1+\dot{m}_7h_7+\dot{W}_{TEG,1}$	$\dot{E}_{D,TEG,1}=\dot{E}_5-\dot{E}_1-(\dot{W}_{TEG,1}+\dot{E}_7-\dot{E}_6)$	$\eta_{II,TEG,1}=(\dot{W}_{TEG,1}+\dot{E}_7-\dot{E}_6)/(\dot{E}_5-\dot{E}_1)$
TEG unit 2	$\dot{m}_{12}h_{12}+\dot{m}_{14}h_{14}=\dot{m}_{12}h_{12}+\dot{m}_{13}h_{13}+\dot{W}_{TEG,2}$	$\dot{E}_{D,TEG,2}=\dot{E}_{12}-\dot{E}_{13}-(\dot{W}_{TEG,2}+\dot{E}_{15}-\dot{E}_{14})$	$\eta_{II,TEG,2}=(\dot{W}_{TEG,2}+\dot{E}_{15}-\dot{E}_{14})/(\dot{E}_{12}-\dot{E}_{13})$

For modeling the TEG unit, the following relations are used [10, 15]:

$$\eta_{TEG} = \eta_{Carnot} \frac{\sqrt{1+ZT_M}-1}{\sqrt{1+ZT_M}+\frac{T_L}{T_H}} \quad (3)$$

$$\eta_{TEG} = \frac{\dot{W}_{TEG}}{\dot{Q}_{ELEGANT}} \quad (4)$$

in which T_L and T_H are temperatures of the cold and hot sides of the TEG, $\dot{Q}_{ELEGANT}$ denotes the efficient liquid-based electricity generation apparatus inside the TEG and ZT_M refers to the figure of merit and is an important parameter since it directly correlates to the thermal to electricity conversion efficiency of the TEG system. η_{Carnot} and $\dot{Q}_{ELEGANT}$ along with ZT_M may be written as follow [10, 16]:

$$\eta_{Carnot} = 1-\frac{T_L}{T_H} \quad (5)$$

$$\dot{Q}_{ELEGANT}(1) = \dot{m}_6(h_7-h_6); \quad (6)$$
$$\dot{Q}_{ELEGANT}(2) = \dot{m}_{14}(h_{15}-h_{14})$$

$$ZT_M = \frac{\psi^2 T_M}{KR} \quad (7)$$

where K and R denote thermal conductivity and resistance. T_M and ψ are defined as:

$$T_M=(T_L+T_H)/2 \quad (8)$$

$$\psi=-\Delta V/\Delta T \quad (9)$$

3.2.Exergoeconomic assessment

Exergoeconomic assessment is conducted for calculating and comparing exergoeconomic parameters along with total product cost of the systems. The cost balance for the k[th] component as a control volume can be written as [17]:

$$\sum \dot{C}_{out,k}+\dot{C}_{w,k} = \sum \dot{C}_{in,k}+\dot{C}_{q,k}+\dot{Z}_k \quad (10)$$

$$\dot{Z}_k = \dot{Z}_k^{CI}+\dot{Z}_k^{OM} \quad (11)$$

$$\dot{C}=c\cdot\dot{E} \quad (12)$$

$$\dot{C}_{out}=c_{out}\cdot\dot{E}_{out} \quad (13)$$

$$\dot{C}_q= c_q\cdot\dot{E}_q \quad (14)$$

$$\dot{C}_w=c_w\cdot\dot{W} \quad (15)$$

where $\dot{Z}_k^{OM}$ denotes the operating and maintenance (O&M) cost.
Likewise, annual levelized capital investment for the k[th] component is [17]:

$$\dot{Z}_k^{CI} = \left(\frac{CRF}{\tau}\right) Z_k \quad (16)$$

where τ denotes the annual plant operation hours and CRF refers to the capital recovery factor [17]:

$$CRF = \frac{i_r(1+i_r)^n}{(1+i_r)^n-1} \quad (17)$$

Afterward, Z_k for the present year (2018) can be calculated:

$$Cost\ at\ present\ year = original\ cost \times \frac{Cost\ index\ of\ the\ present\ year}{Cost\ index\ of\ the\ base\ year} \quad (18)$$

The cost equations (Z_k) for the components of the proposed systems are presented in Table 2.

Table 2. Investment cost (Zk) for each component of the proposed system [11, 17]

Component	Z_k
ORC Pump	$Z_{ORC,pu} = a_1 (\dot{W}_{ORC,pu})^{0.71}$ a_1=3540 \$/kW
ORC Turbine	$Z_{ORC,t} = a_2 (\dot{W}_{ORC,t})^{0.75}$ a_2=4750 \$/kW
ORC Evaporator	$Z_{ORC,ev} = a_3 (A_{ORC,ev})^{0.85}$ a_3=309.14 \$/m^2
ORC Condenser	$Z_{ORC,Cond} = a_4 (A_{ORC,Cond})^{0.6}$ a_4=516.62 \$/m^2
TEG	Z_{TEG}=$a_5\dot{W}_{TEG}$ a_5=1500 \$/kW

Cost balance equations for each component of the proposed systems are listed in Table 3.

3.3.Exergoeconomic evaluation

To have a better outlook for the trade-offs between the technical and economic criteria, an exergoeconomic evaluation of the proposed models is performed. The cost of unknown streams and important exergoeconomic parameters can be found by solving cost balance and auxiliary equations for the components. Important exergoeconomic parameters are defined as follow:

$$c_{F.k} = \frac{\dot{C}_{F.k}}{\dot{E}_{F.k}} \quad (19)$$

$$c_{P.k} = \frac{\dot{C}_{P.k}}{\dot{E}_{P.k}} \quad (20)$$

$$\dot{C}_{D.k} = c_{F.k}\dot{E}_{D.k} \quad (21)$$

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D.k} + \dot{C}_{L.k}} \quad (22)$$

where $c_{F,k}$, $c_{P,k}$, $\dot{C}_{D,k}$, and f_k are the unit cost of fuel, the unit cost of product, cost rate of exergy destruction and exergoeconomic factor, respectively.

3.4.Performance examination

The second law of thermodynamics is implemented to examine exergy efficiency of the proposed models. Additionally, the total cost associated with the product as a decent. Economic indicator is used to evaluate total product cost of the systems. Total exergy efficiency of the proposed model and total product cost can be respectively defined as:

$$\eta_{II} = \frac{\dot{W}_{TEG,1} + \dot{W}_{TEG,2} + \dot{W}_t - \dot{W}_{pu}}{\dot{E}_{10}} \quad (23)$$

$$c_{p,tot} = \frac{\sum_{i=1}^{n_k} \dot{Z}_k + \sum_{i=1}^{n_F} \dot{C}_{F_i}}{\sum_{i=1}^{k} \dot{E}_{P_i}} \quad (24)$$

Furthermore, the payback period of the systems can be calculated as follows:

$$PP = \frac{\sum_{i=1}^{n_k} Z_k}{\dot{W}_{net} \times electricity\ cost \times \tau} \quad (25)$$

In this paper, electricity cost is considered equal to 0.1 $/kWh.

4.Results and discussion

Validation and parametric study of the effective parameters of the proposed system are evaluated in this section. Accordingly, the influence of the ORC working fluid is examined and the best fluid is chosen in the aspect of exergy and exergoeconomic viewpoints.

4.1.Verification

To verify modeling of the TEG unit, the present model is compared to that of Ziapour et al. [12] as can be seen in Fig.2. According to the figure, there is a decent agreement between the results.

Table 3. Cost balances and auxiliary equations for each component

Component	Cost balance	Auxiliary equation
Pump	$\dot{C}_1+\dot{C}_9+\dot{Z}_{Pu}=\dot{C}_2$	$c_8=c_9$
Turbine	$\dot{C}_4+\dot{Z}_t=\dot{C}_5+\dot{C}_8$	$c_4=c_5$
Condenser (simple ORC)	$\dot{C}_5+\dot{C}_6+\dot{Z}_{cond}=\dot{C}_1+\dot{C}_7$	$c_5=c_1$, $c_6=0$
TEG unit 1	$\dot{C}_5+\dot{C}_6+\dot{Z}_{TEG}=\dot{C}_1+\dot{C}_7+\dot{C}_{TEG}$	$c_8=c_{TEG}$, $c_5=c_1$, $c_6=0$
Evaporator and superheater	$\dot{C}_2+\dot{C}_{10}+\dot{Z}_{ev}=\dot{C}_4+\dot{C}_{12}$	$c_{10}=c_{12}$, $c_{10}=5$ $/GJ
TEG unit 2	$\dot{C}_{14}+\dot{C}_{12}+\dot{Z}_{TEG}=\dot{C}_{13}+\dot{C}_{15}+\dot{C}_{TEG}$	$c_9=c_{TEG}$, $c_{14}=0$

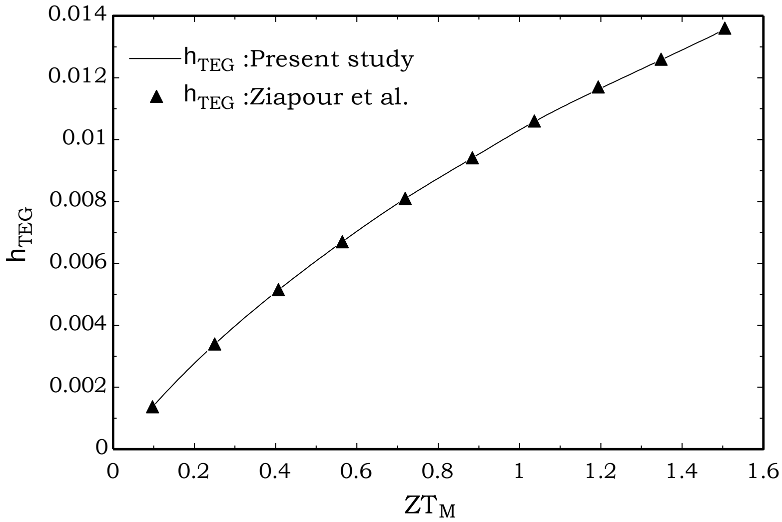


Fig. 2 .Verification of the present TEG results with the available numerical data

Table 4 shows the simulation results for the current ORC compared to the available data [18, 19].

4.2.Parametric study

In this section, the influence of the effective design parameters on exergy efficiency, total associated cost of the products, power output, and TEGs power output is investigated. The input parameters as the base case are tabulated in Table 5. In this section, model (a) is considered as simple ORC and model (b) refers to the new proposed model.

Effect of the turbine inlet pressure on the exergy efficiency and total product cost is shown in Fig.3(a). As the figure illustrates, by increasing the turbine inlet pressure from 8 to 28 bar, exergy efficiencies initially increase and thereafter decrease.

Table 3. Comparison of important simulation results with literature

Parameter	**Literature** [18, 19]	**Present model**
Power (kW)	48.57	48.51
First law efficiency (%)	12.6	12.58
Second law efficiency (%)	46.8	46.73

Table 4. Input parameters values for the proposed systems

Parameter	**Value**	**Parameter**	**Value**
T_0 (°C)	15	ΔT_{sup}	20
P_0 (bar)	1.013	$\Delta T_{p,p}$	5
T_6 (°C)	170	$CETD_{TEG,1}$	5
$\dot{m}_6$ (kg/s)	1	$CETD_{TEG,2}$	10
η_p	0.9	$ZT_{M,1}$	0.8
η_t	0.85	$ZT_{M,2}$	0.8
P_4 (bar)	15	$\dot{m}_{14}$ (kg/s)	3

On the contrary, total product cost of the system decrease at first and thereafter increase. Therefore, there is an optimum operating condition at P_4=14 bar in the aspect of exergy and exergoeconomic. Figure 3 (b) shows that similar to the exergy efficiency trend, net output power rises initially up to P_4=14 bar and drops after that. Moreover, the power output of TEG1 increases by raising the turbine inlet pressure while the power of TEG2 initially increases up to P_4=12 bar and decreases thereafter.

As depicted in Fig.4(a), by altering the cold end temperature difference (CETD) of TEG1, the exergy efficiency changes notably. The increment in CETD will decrease the exergy efficiency of the models and increase total product cost. Additionally, as shown in Fig.4(b), by increasing the CETD from 2 to 15 °C, the net power output of the models decreases linearly. On the other hand, by increasing the CETD, the TEGs power output increase since the temperature of the hot side of the TEGs increase.

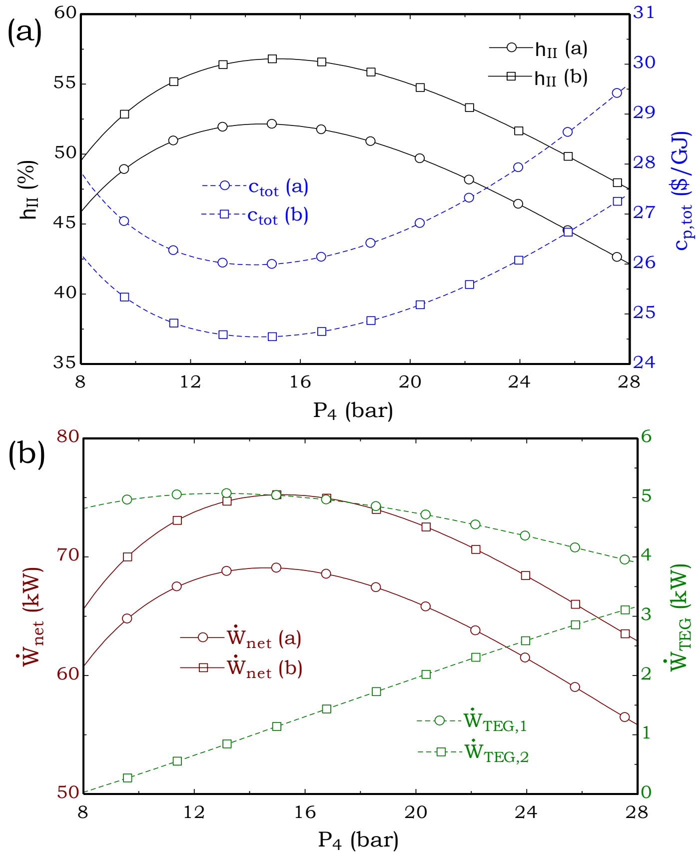
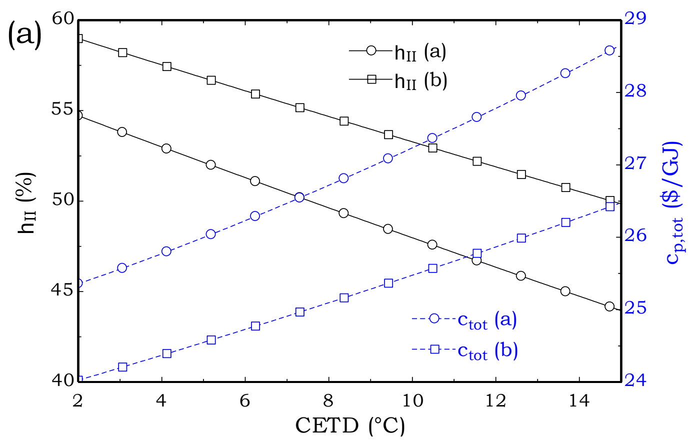


Fig.1. Effect of increasing the turbine inlet pressure on a) exergy efficiency and total cost b) net power output and TEG power output



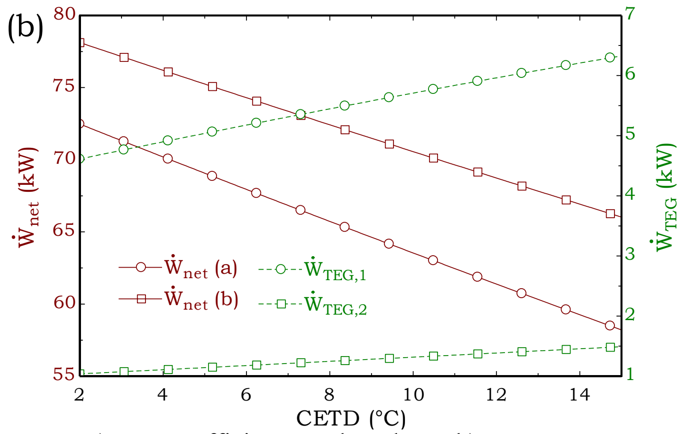


Fig.2. Effect of the CETD on a) exergy efficiency and total cost b) net power output and TEG power output

The figure of merit (ZTM) as a key parameter, which indicates the internal conversion efficiency of the TEG, can affect the exergy efficiency and total cost of the models by much. As shown in Fig.5 by raising the parameter from 0.2 to 1.6, exergy efficiency, net power output, and the TEG power output of the proposed system increase while the total product cost decreases. Increasing the figure of merit while enhancing the efficiency of the TEG, is expected to enhance the performance indicators of the system.

Pinch point difference temperature ($\Delta T_{p,p}$) of the evaporator is another key parameter which can affect the results (Fig.6). By increasing this parameter, exergy efficiencies and net power outputs decrease while the total products costs are expected to increase. Additionally, by raising the parameter from

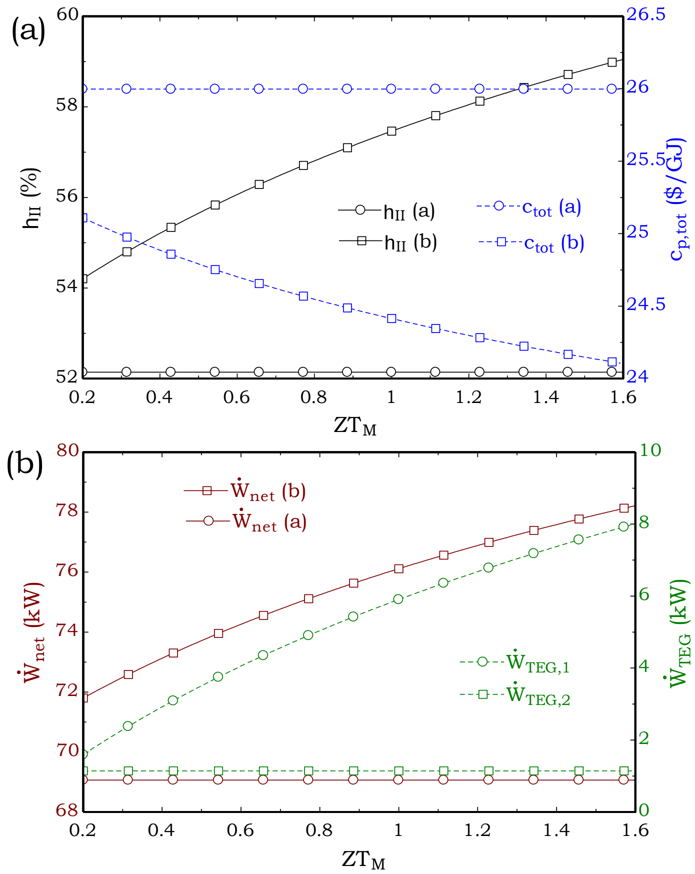


Fig.3. Effect of increasing the figure of merit on a) exergy efficiency and total cost b) net power output and TEG power output

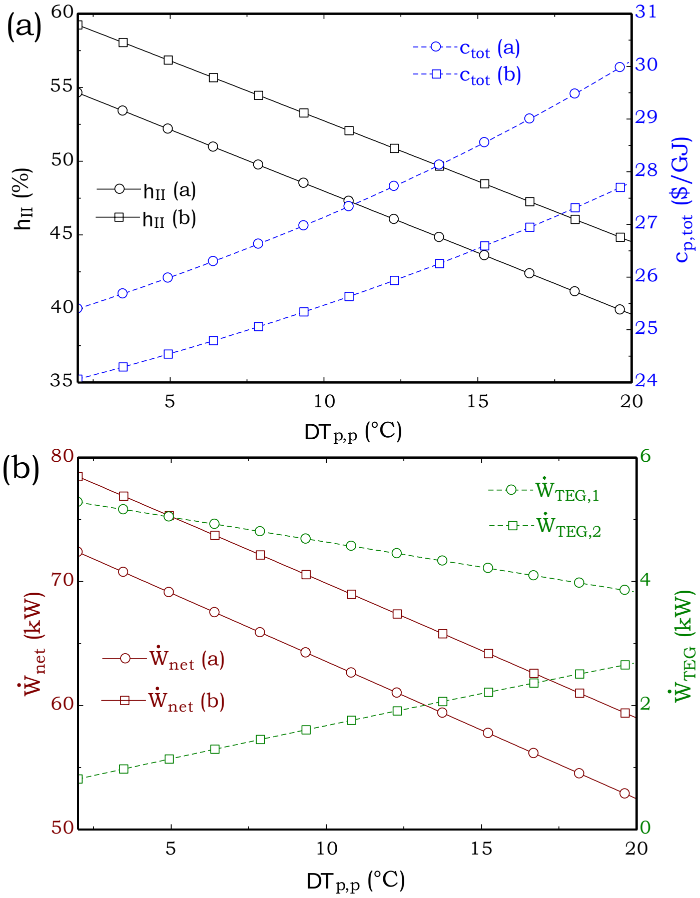
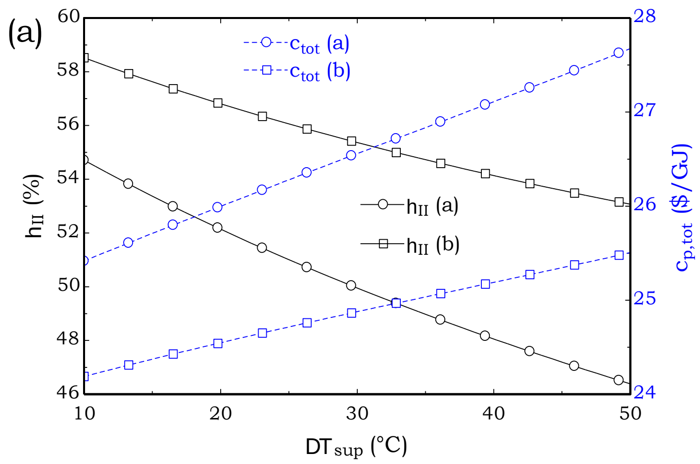


Fig.4. Effect of increasing pinch point temperature difference on a) exergy efficiency and total cost b) net power output and TEG power output

2 to 20 °C, the power production by TEG1 decreases while TEG2's power output increases.

The influence of the superheater temperature difference (ΔT_{sup})—which is closely connected to the turbine inlet temperature—on exergy efficiency and total product cost of the three proposed models is depicted in Fig.7(a). By increasing the ΔT_{sup}, exergy efficiencies along with the net powers would decrease (since the turbine power output decreases) while the TEG power will drop. This is justified because increasing the superheater temperature will rise the temperature of the hot side of the TEGs so TEG power outputs increase.



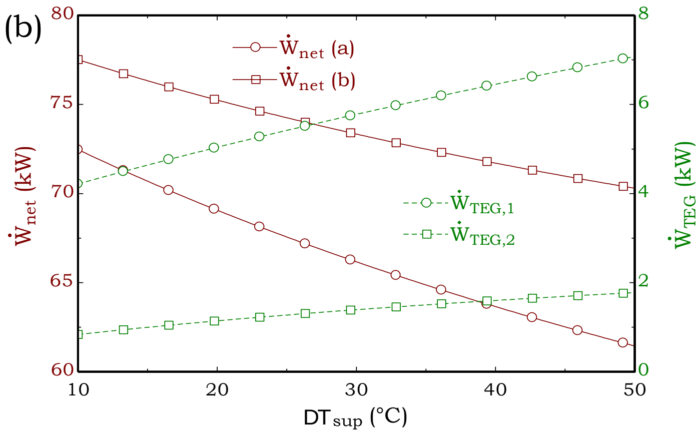


Fig.5. Effect of superheater temperature difference on a) exergy efficiency and total cost b) net power output and TEG power output

Heat source temperature is another effective parameter and by increasing it, exergy and energy efficiency of the models increase while the total cost decrease (Fig.8). Additionally, by increasing the heat source temperature, the net power output, exergy efficiencies, and the TEGs power output increase since more heat source temperature is equivalent with more available heat for the steam generator. Besides, inference form the figure is that raising the heat source temperature will decrease the TEG2 power output while TEG1 power generation increases. The decrement of the TEG2 power generation is justified because the temperature difference between the hot and cold side of the TEG decreases so the power generation drops.

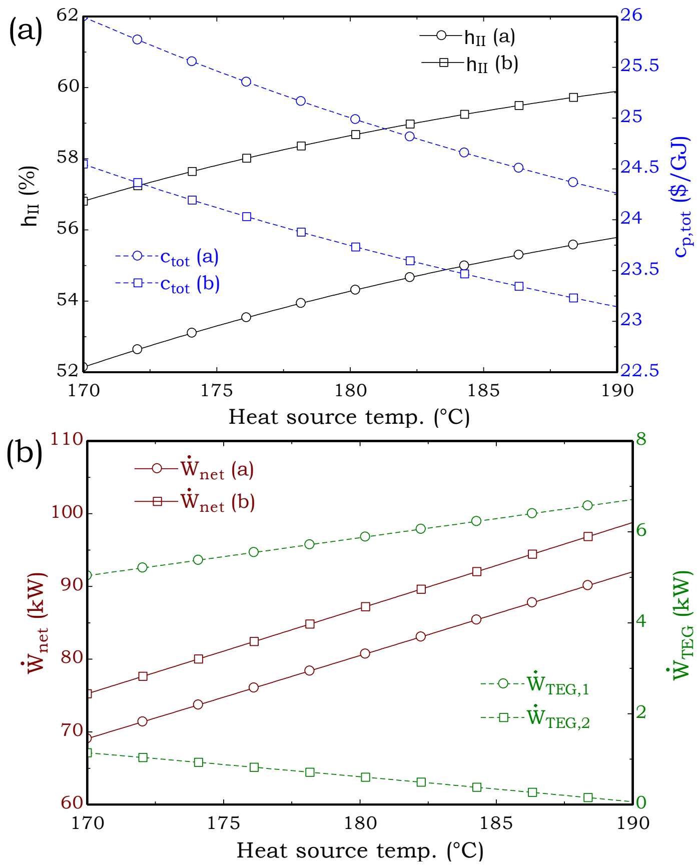


Fig.6. Effect of geothermal brine temperature on a) exergy efficiency and total cost b) net power output and TEG power output

As Fig.9 reveals, the mass flowrate of geothermal brine could also be an effective parameter since by increasing it exergy efficiency of the simple ORC remains constant while exergy efficiency of the proposed model would decrease. Such trend can be described by the fact that under such conditions the denominator of Eq. (23) increases at a faster rate than the nominator. Moreover, by raising the mass flowrate, the net power outputs increase while the total product costs would decrease. Additionally, increase in TEG1 power generation is expected by increasing the heat source mass flowrate, since in such conditions the working fluid with higher enthalpy enters the TEG.

Effect of TEG2 cooling water mass flowrate is depicted in Fig.10. As the figure shows, by increasing the cooling water mass flowrate, there is an optimum point from exergy/exergoeconomic viewpoints on $\dot{m}_{14}$=3.5 kg/s since at such mass flowrate, total exergy efficiency and product cost are at their optimum values. Moreover, at such mass flowrate, total power output and TEG2 power generation are at their maximum values.

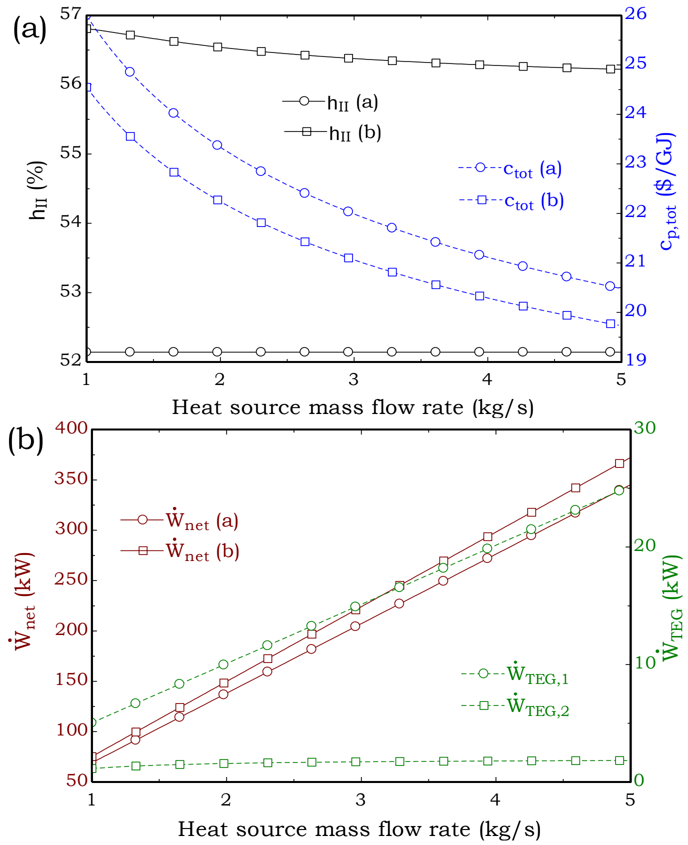
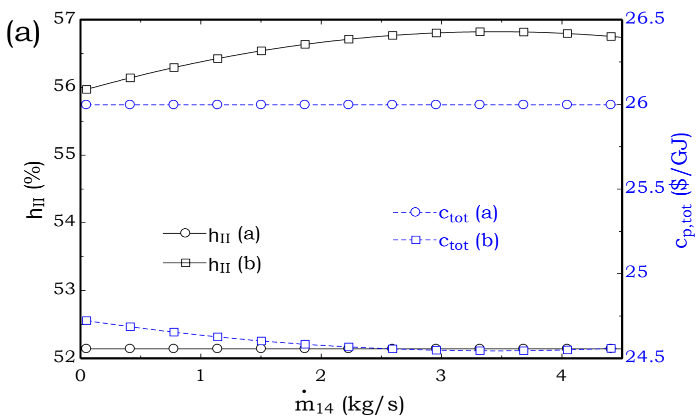


Fig.7. Effect of geothermal brine mass flowrate on a) exergy efficiency and total cost b) net power output and TEG power output



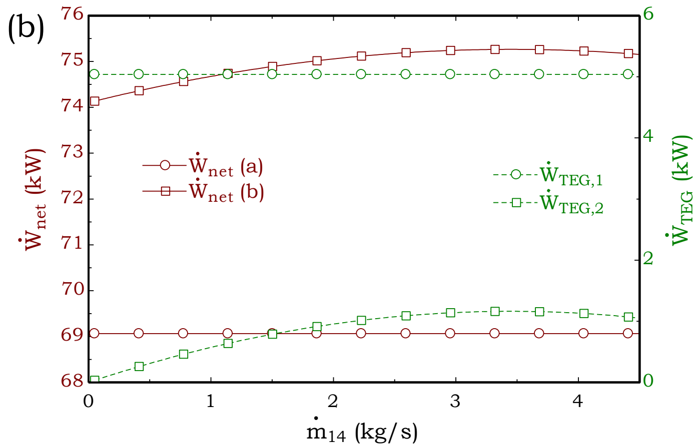


Fig.8. Effect of the mass flowrate of state 14 on a) exergy efficiency and total cost b) net power output and TEG power output

Effect of the figure of merit for TEG2 is illustrated in Fig.11. It can be inferred from the figure that by raising the merit from 0.2 to 1.6, the exergy efficiency, power generation of the TEG2 and net power output increase. Exergy efficiency and power generation of the simple ORC is also provided for a better comparison of the models.

The cold end temperature difference of the TEG2 can affect the results considerably. As Fig.12 shows, there is an optimal point at the cold end temperature of 10 °C since at this point, exergy efficiency is maximum while total product cost would be minimal. Similar trends are expected for total power output and TEG power generation. At *CETD*=10 °C, TEG operates at its most effective condition so the power generation of the TEG unit would be maximum.

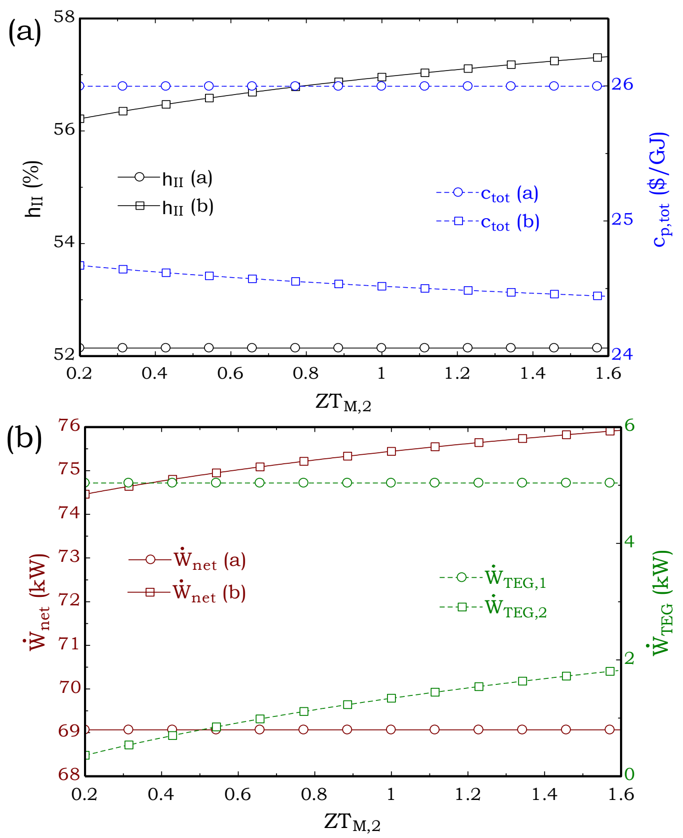


Fig.9. Effect of the TEG2 figure of merit on a) exergy efficiency and total cost b) net power output and TEG power output

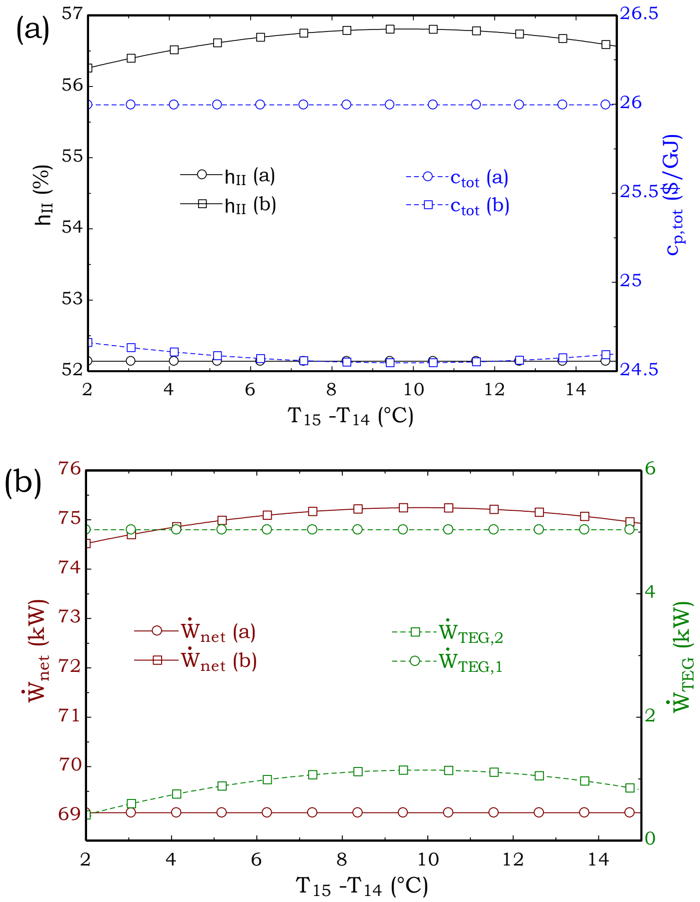


Fig.10. Effect of Temperature difference of TEG2 cooling fluid on a) exergy efficiency and total cost b) net power output and TEG power output

4.3.Exergy and exergoeconomic analysis

Thermophysical and exergoeconomic values of each stream of the proposed systems are listed in Table 6.

Exergoeconomic parameters such as the cost of exergy destruction, the product and fuel cost rates, exergy efficiency and exergoeconomic factor for all components are summarized in Table 7. The exergoeconomic factor (f_k), which is the criterion for evaluating the relative importance of exergy destruction and capital investment costs, plays an important role in the exergoeconomic analysis. The higher values of exergoeconomic factor reveal that the operating and maintenance cost is more effective than the cost of exergy inefficiencies. For example, the high level of f for the turbine shows that reducing the capital investment cost would be cost effective at such equipment. For the turbine, the exergoeconomic factor reveals that 92.43% of the relative cost difference is caused by the operating and maintenance cost. For these components, a reduction in the operating and maintenance cost is suggested to avoid lower exergy efficiency and higher cost of destruction. The low value of the exergoeconomic factor is equivalent to the higher value of $\dot{Z}_k+\dot{C}_D$, which is the result of higher exergy destruction costs and more irreversibility. For the equipment with the exergoeconomic factor below 50%, a high value of exergy destruction and lower operating and maintenance costs are expected.

Important performance and economic indicators of the simple ORC and the proposed integrated system along with the power output of the TEG units are presented in Fig.13. As the figure shows, the proposed integrated system has higher exergy efficiency, lower total product cost, lower payback period, and higher power output compared to the simple ORC cycle. The payback period of the system is calculated from Eq. 26.

The comprehensive parametric study reveals that the proposed integrated system is a promising method to enhance the power generation, decrease the total product cost and

Table 5. Thermophysical and exergoeconomic parameters in each stream of the proposed systems

State	*T* (K)	*P* (bar)	*h* (kJ/kg)	$\dot{m}$ (kg/s)	$\dot{E}$ (kW)	*c* ($/GJ)	$\dot{C}$ ($/h)
1	293.2	1.809	55.73	2.516	14.38	7.792	0.4035
2	293.2	15	56.73	2.516	16.64	13.58	0.8137
3	376.4	15	233.5	2.516	99.19	7.792	2.782
4	396.4	15	252.3	2.516	111.2	7.792	3.12
5	344	1.809	223.9	2.516	28.96	7.792	0.8125
6	288.2	1.013	63.01	9.990	0	0	0
7	298.2	1.013	104.8	9.990	7.088	8.702	0.222
8	–	–	–	–	71.57	23.16	5.966
9	–	–	–	–	2.506	23.16	0.2089
10	443.2	8.915	719.3	1.000	132.5	5	2.384
11	432.3	8.915	671.9	1.000	116.4	4.997	2.094
12	327.3	8.915	227.3	1.000	10.98	5	0.1976
13	297	8.915	100.6	1.000	1.345	5	0.02421
14	288.2	1.013	63.01	3.000	0	0	0
15	298.2	1.013	104.8	3.000	2.128	17.09	0.131

Table 6. Exergoeconomic parameters of each component of the combined cycle

Component	$\dot{E}_F$ (kW)	$\dot{E}_P$ (kW)	$\dot{E}_D$ (kW)	η_{II} (%)	$\dot{C}_F$ ($/h)	$\dot{C}_P$ ($/h)	$\dot{C}_D$ ($/h)	$\dot{Z}$ ($/h)	*f* (%)
Condenser	14.58	7.173	7.408	49.2	0.409	0.509	0.2078	0.1001	32.5
Turbine	82.25	71.57	10.68	87.01	2.307	5.966	0.2996	3.659	92.43
Pump	2.506	2.261	0.225	90.24	0.209	0.410	0.0204	0.2013	90.8
Evaporator	121.5	94.57	26.91	77.85	2.187	2.306	0.4844	0.1195	19.79
TEG 1	14.58	12.13	2.455	83.16	0.409	0.642	0.0688	0.233	77.19
TEG 2	9.631	3.271	6.36	33.96	0.173	0.226	0.1145	0.0528	31.57

payback period, and increase exergy efficiency of the simple ORC system. So, the newly proposed system can be further developed since it is more suitable from exergy/exergoeconomic viewpoints compared to the simple ORC cycle.

5.Conclusion

In the present work, an integrated renewable energy plant based on geothermal ORC cycle has been proposed consisting of two thermoelectric generators (TEGs). First TEG unit is established instead of the condenser and the second one is installed to recover the waste heat of the geothermal brine. A parametric study has been applied on the simple ORC and the proposed integrated system to investigate the influence of the effective parameters on the exergy/exergoeconomic indicators. Moreover, the payback period of the systems has been calculated to have a better outlook of the comparison of the systems. Main conclusions of this study could be summarized as:

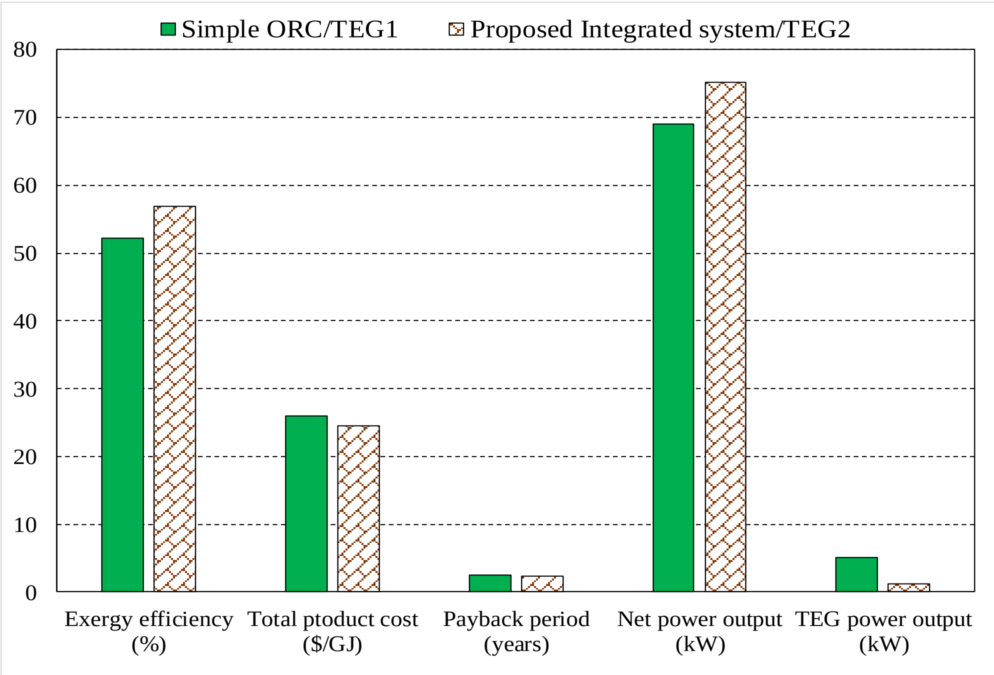


Fig.11. comparison of the simple ORC and the proposed integrated system from thermodynamic and thermo-economic viewpoints

- Exergy efficiency of the proposed system would be 56.81% in the base case (4.67% higher than the simple geothermal based ORC system).
- Total product cost of the proposed integrated system is 24.55 $/GJ at the base case (5.5% lower than simple ORC).
- The payback period of the suggested system is 2.422 years (15 days lower than the simple ORC cycle).
- The net power output of the model (b)—the novel proposed system—is 75.24 kW (9% higher than simple ORC cycle).

Power generation of the TEG1 and TEG2 units would be 5.039 kW and 1.142 kW. TEG1 is established to recover the waste heat of the condenser while TEG2 is installed to exploit the waste heat of the geothermal brine.

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