

4E Analysis of a Geothermal-Based Multigeneration System

Hanaa Kadhim Kareem Alsabahi | Majid Abbasalizadeh* 

Ata Chitsaz  | Morteza Khalilian 

Department of Mechanical Engineering, Urmia University, Urmia, Iran

* Corresponding author, Email: m.abbasalizadeh@urmia.ac.ir

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Abstract

This study aims to assess a new geothermal multisource energy system upon a comprehensive 4E framework of the Energy, Exergy, Economic, and Environmental aspects. The system integrates numerous technologies for energy conversion and use, which includes an Organic Rankine Cycle (ORC) coupled with a Thermoelectric Generator (TEG), a Single-Effect Absorption Chiller (SEAC), a Proton Exchange Membrane (PEM). A distinct benefit of the system is its use of a TEG instead of the usual condenser, allowing waste heat to be converted into extra electricity via the Seebeck effect, thus enhancing the efficiency of energy conversion without using extra power. The multigeneration system is designed to produce electricity, heating, cooling, hydrogen and freshwater which makes it perfect for regions endowed with geothermal resources and various energy demands. The simulation results demonstrating a comprehensive thermodynamic simulation indicate that the system has 66.42% energy efficiency and 77.12% exergy efficiency. According to the exergoeconomic analysis, the overall capital and the maintenance cost expended is mostly driven by the turbines and geothermal unit, although optimization possibilities can be made within heat exchangers and condensers. The optimization of the heat recovery and design of cultural thermal solutions can not only reduce energy losses but also increase performance and benefit the overall costs, ensuring thermal efficiency. In general, activity environment index of the system 0.03206 corresponds to minimal direct ecological disturbance, and its exergy sustainability coefficient is 0.0711, which points out the possibility of further enhancement of sustainability. This geothermal setup is poised excellently as an efficient, sustainable and multipurpose energy solution as per results.

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1 Introduction

The ever-increasing global energy need, fueled by rapid industrialization, urbanization and population explosions, has created serious environmental and economic issues [1]. Fossil fuels, which have been the conventional source of fuel, are gas emitters, environmental destroyers, and volatile market players. As a result, the ability to switch to sustainable and cleaner forms of energy is an important worldwide goal. From different renewable energy sources, geothermal energy is a solution with a high potential because it is continuous, has a high-capacity factor and minimal environmental implications. Geothermal is the use of the Earth's internal heat which can be used on several fronts, including electricity generation, direct heating, and certain industrial processes. In contrast to intermittent energies of the sun and wind, the supply of geothermal energy can be considered stable and uninterrupted; it suits base-load installations very well [2]. Although geothermal technology has promising capabilities, its deployment has usually been impeded by the constraints of geography and high upfront cost. Nevertheless, drilling, reservoir modeling and system integration have continuously increased the viability of geothermal projects. At the same time, there is growing interest in multigeneration (or polygeneration) systems, which aim to deliver multiple outputs from a single primary energy source – such as electricity and space heating, cooling, desalinated water, and even hydrogen production [3]. The blending of multigeneration concepts with geothermal energy yields a distinct opportunity for optimal utilization of resources, curtailment of wastage of energy and enhanced efficiency of the whole system. Multigeneration systems enhance the exergy efficiency through cascading exploitation of thermal energy at various temperature levels and participation in energy conservation initiatives. The assessment of performance of such complex energy systems calls for multifaceted techniques. The 4E analytical framework that includes Energy, Exergy, Economic, and Environmental analysis, is becoming an all-over accepted methodology on this issue. The focus in the energy analysis is on the quantitative assessment of energy flows within the system according to the first law of thermodynamics. Exergy analysis on the basis of the second law determines the quality/ or usability of energy thus identifying inefficiency and irreversibility. The economic analysis establishes efficiency and feasibility in terms of capital investment, operating cost, and economic returns. Finally, environmental analysis assesses the ecological footprint: emissions of greenhouse gases and resource depletion, which guarantees

the system's harmony with goals of sustainability. Recent literature has revealed growing voices in answering the development and optimization of geothermal-based multigeneration system through the 4E framework [4]. Researchers have explored several options- from Organic Rankine Cycles (ORCs) to Kalina cycles to absorption cooling technologies- and have reported promising results in terms of energy efficiency and carbon reduction. Nevertheless, system performance is highly dependent on temperature of the resources, system design, and regional energy demand. Therefore, in order to adapt these systems to particular applications and geographic areas, detailed modeling and analysis are necessary.

Haider et al. [5] developed a geothermal-dependent multigeneration system that can produce electricity, heat, cooling, fresh water as well as hydrogen at the same time. The system combines a power generation unit and desalination, electrolysis units, which is optimal for energy utilization that varies with different outputs. It was able to realize energy and exergy efficiencies of 54.22% and 38.96% respectively while it produced 103 MW of electricity 0.1266 kg/s of hydrogen and 37.6 kg/s of fresh water. The study proves the ability of the system to deliver utility in a geothermal rich region in an efficient and sustainable way. Ambriz-Díaz et al. [6] investigate a geothermal driven multigeneration system that operates at various hierarchical levels within a cascade arrangement. This configuration enabled better energy utilization as the heat quality was aligned with end-use needs, which corresponded to 9.29% increase of energy output and higher exergetic efficiency than that of classical single-level systems. The approach also minimized thermal losses and increased the overall system sustainability. Rostamzadeh et al. [7] investigate a hybrid system combining biogas and geothermal energy sources for multigeneration applications. Multi-criteria optimization led to a 12.07% increase in thermal efficiency and a 5.16% improvement in exergy efficiency. The optimized system also reduced overall product costs by 3.7% and lowered greenhouse gas emissions by 4.44%, demonstrating its potential for both economic and environmental benefits in regions with access to both resources. Ünal et al. [8] do a 4E analysis of an underfloor heating system coupled with with geothermal heat pump for greenhouse heating. The system recorded an energy efficiency of 77.85% and exergy efficiency of 30.61%. It also decreased CO₂ emissions by 909.75 kg during a 4-month heating season with compared to a natural gas boiler; this further showed its environmental and energy efficient benefits.

Hosseini et al. [9] provide an outline of the process for assessing the techno-economic-environmental

performance of multi-vector energy networks where geothermal energy storage may be involved. The study revealed that combining geothermal with solar and wind lowered energy imports with 28%, decreased operational costs by 12%, and reduced CO₂ emissions by 18%, a manifestation of possibilities for more sustainable as well as cost effective energy systems. Ratlamwala et al. [10] examine a geothermal-based system that involves a quadruple-effect absorption cycle to maximize recovery of energy. When the turbine was increased to higher pressures, the system produced a remarkable power increase and overall system efficiency as the electrical power generation increased by 18.5%. The design also showed adaptability as it produced cooling, heating and potable water. This capability led to fuel savings of 25% in comparison to conventional systems emphasizing the system's promise for enhanced efficiency and multiple energy use.

Azariyan et al. [11] introduce a high-performance geothermal-based multigeneration system which is combined by a Kalina cycle, and a water-ammonia absorption refrigeration cycle amiss a proton exchange membrane electrolyzer. Their thermodynamic and exergoeconomic assessment reveals that the system is capable of generating 258.6 kW of cool down, with thermal and exergy efficiencies of 22.28% and 21.37% respectively. The research demonstrates how such systems may be useful in energy production with high efficiency levels as well as sustainability. Lin et al. [12] suggest a geothermal-responsive multigeneration system which combines a double-flash geothermal cycle, a Kalina power cycle, LNG cold energy recovery, and hydrogen production. The performance of the system is evaluated via a 4E analysis resulting in energy efficiency 28.91% and exergy efficiency of 76.39%. It generates 15,260 kW cooling, 30,640 kW of power and 20.16 kg/h of hydrogen while cutting off CO₂ by 189,898 kg per year. The system shows great promise for sustainable energy generation and better exploitation of resources.

The study by Abdollahi et al. [13] is dedicated to the exploitation of geothermal resources allotted to multi-generation purposes, namely, hydrogen production and chilling with the help of the absorption refrigeration cycle implementation. It aims to show the novel utilization of geothermal energy as both a form of liquid hydrogen storage as well as a source of power. Along with a cost economic analysis, exergy and energy analyses are also provided that have estimated the total system cost at a value of US\$1.49 million and resulted in a specific energy consumption of 8.51 kWh/kg liquid hydrogen. An article by Et Al. [14] looks at a multigenerational energy system where energy is provided through geothermal output of energy plants and,

in conjunction, the use of biomass as a heat source. The design combines domestic water heating and absorption refrigeration systems of both the single and double-effect absorption types. The thermodynamic, exergy, and techno-economic frameworks are used to analyze optimal conditions under which exergy efficiency is 24.88 and a payback time of 4.92 years with a net present value of 4.265 million.

In recent literature, Francisco-Hernandez et al. [15] report a succinct survey on geothermal and solar energy combinations in district cooling systems (DCS) to use sustainable building energy. The report outlines the two major geothermal systems cascade configurations and absorption chiller technologies and assessed the Mexican thermal endowment that is applicable in space conditioning. The paper enhances the discussion on the environmentally friendly cooling technology as it presents the viability, efficiency, and scalable renewable-energy-based cooling solutions. Shakir Hussein et al. [16] do an extensive analysis of an integrated multi-functional system using a combination of solar energy source and geothermal energy source to produce several products simultaneously including cooling, heat, electricity, hot water, hydrogen, and desalinated water. This system has a PEM electrolyzer, reverse-osmosis desalination system, organic-Rankine, absorption refrigeration system, as well as, domestic water heater. In simulation modeling with the Engineering Equation Solver (EES) program, the higher nanoparticle loadings in the electrolyzer intensify turbine generation, but also reduce capacity in thermoelectric-generation. Also, it is demonstrated that performance of the system has significantly increased with higher solar irradiance.

Mejbel Ghrairi et al. [17] consider a multi-generation set-up consisting of photovoltaic thermal collectors, and ground-coupled heat exchangers with two organic Rankine cycles, and complementing tri-generation with these modules used as thermo-electric generators to provide electricity. Their calculations-carried out using EES software-yield energetic and exergetic efficiencies of 41.58% and 25.61%, respectively, and produce 493.1 kg/day of hydrogen. n-pentane was found to be the best working fluid. Chidire et al. [18] suggest a hybrid of cooling power system (GCCPS) that is based on geothermal energy, forming an organic Rankine cycle (ORC) and absorption chiller. The performance of the system at long length (30 years) is analyzed by the authors who show a trade-off in electricity and cooling outputs that is highly controlled by ORC outlet temperatures. Greenhouse-gas emission savings can be shown by a detailed life-cycle analysis to be over 14 times those of district-cooling systems. Wu et al. [19] report an Organic Rankine Cycle

(ORC) in combination with an Ejector Expansion Refrigeration Cycle (EERC) to use low-temperature heat sources. Single and dual condenser dynamic models are built and the performance of the system is found to be more sensitive to the perturbation of the ORC subsystem. It is then followed by a multi-device co-operative control strategy that magnifies the cooling capacity of the system up to 9.29% in the face of geothermal water disturbances. Toker [20] includes illustration and evaluation of a sophisticated solar-and-geothermal-energy-supported multigeneration facility producing electricity, cooling, hydrogen, fresh water, heating. Few technologies are integrated in the facility, which include: solar-fuel-gasification - Paddle-Type Steam-Cracker (SFG-PTSC), thermodynamic cycles (supercritical CO₂ Brayton [sCO₂ Brayton] and organic-Rankine cycles [ORC]) and Proton-Exchange-Membrane electrolyzer (PEM). Its overall exergetic and energetic efficiency is 0.526 and 0.499, respectively, and its maximum exergy irreversibility in the SFG plant.

This research presents a new geothermal multigeneration system evaluated through extensive 4E (Energy, Exergy, Economic, and Environmental) analysis. Despite the common discussion in publications of energy, exergy, and economic aspects, the environmental assessment is rather underused – this work contributes by focusing more on the environmental dimension in comparison with the others. One of the main innovations that arise in the proposed system is the integration of thermoelectric generators (TEGs) where the role played by the conventional condenser was performed before, and this now allows additional generation of electricity, by harvesting of the waste heat from the geothermal source, with no extra energy as input. This improves system performance and utilization of exergy overall. While this study is based on theoretical modeling rather than empirical data, it contributes meaningfully to conceptual developments and optimization for geothermal driven multigeneration with improved sustainability and performance.

2 Methodology

2.1 Process description

The proposed system combines subsystems to conserve geothermal energy to generate both electricity and cooling, reheating, hydrogen, and fresh water. Network of Organic Rankine Cycle (ORC)/thermoelectric generator (TEG), Single-Effect Absorption Chiller (SEAC), Proton Exchange Membrane (PEM) electrolyzer, and Reverse Osmosis (RO) desalination unit. These subsystems, as shown in Figure 1, interconnect

each other to make optimum use of energy conversion and dissemination.

Geothermal fluid taken out from a well is first processed to eliminate gases and particles. The fluid is divided in to two streams after treatment: one conduces heat toward the ORC subsystem which produces electricity whereas the other provides thermal energy for the SEAC subsystem to deliver cooling. The two streams are then combined for low grade heating of residential and water heating requirements. After all the thermal energy has been used, the geothermal fluid is reinjection to the reservoir in order to conserve pressure and sustain long-term sustainability. This cascading process of this geothermal energy escalates system efficiency as the higher temperature heat is initially consumed, and then the low-grade heat is re-used for the thermal purpose, thereby ensuring a culmination of optimum results.

R123 is a choice working fluid for the ORC subsystem owing to the thermodynamic advantages and environmentally friendly of R123. The working fluid is pressurized in the pump and in the geothermal heat exchanger heated to become superheated vapor. This vapor then expands across a turbine thus producing electricity. Heat generated from the turbine is delivered in to a TEG, which uses the waste heat to produce additional electricity; this is achieved through exploitation of the Seebeck effect, which in turn increases energy recovery and does away with normal cooling systems. The electricity produced by the ORC and TEG subsystems powers the power electrolyzer which splits deionized water into hydrogen. This hydrogen may be stored for subsequent deficits or may serve as a pure fuel, promoting flexibility of system. The electricity produced is also used to run an RO desalination unit that provides fresh water using the pressure driven reverse osmosis method. In this process seawater is pushed through semi permeable membranes separating fresh water from brine.

SEAC subsystem is dependent on LiBr–H₂O working pair in terms of absorption cooling. Heat is passed to the absorbent through geothermal energy, and consequently hydration vapor of the solution is desorbed. Vapor condensation is then done to absorb the thermal energy present in the surrounding environment and the process is followed by evaporation and isenthalpic expansion using a throttling valve. This vapor, is then reabsorbed by the LiBr solution and is continuous absorption-desorption cycle. It is an especially favorable scheme where the cooling needs can be demanding and unbroken, as is the case in hospitals, and considering reduced environmental effects. Heat recovery stage has been incorporated to improve on the system efficiency in which all waste heat generated by the

ORC and SEAC subsystems is directed into a mixing chamber and then to a secondary unit to be used by the heat. This reclaimed low-grade thermal energy is used in domestic hot water generation and heating of

space. After total consumption of its thermal potential, the generated geothermal fluid is re-injected back to the reservoir to preserve the reservoir pressure, and sustainably protract resource survival.

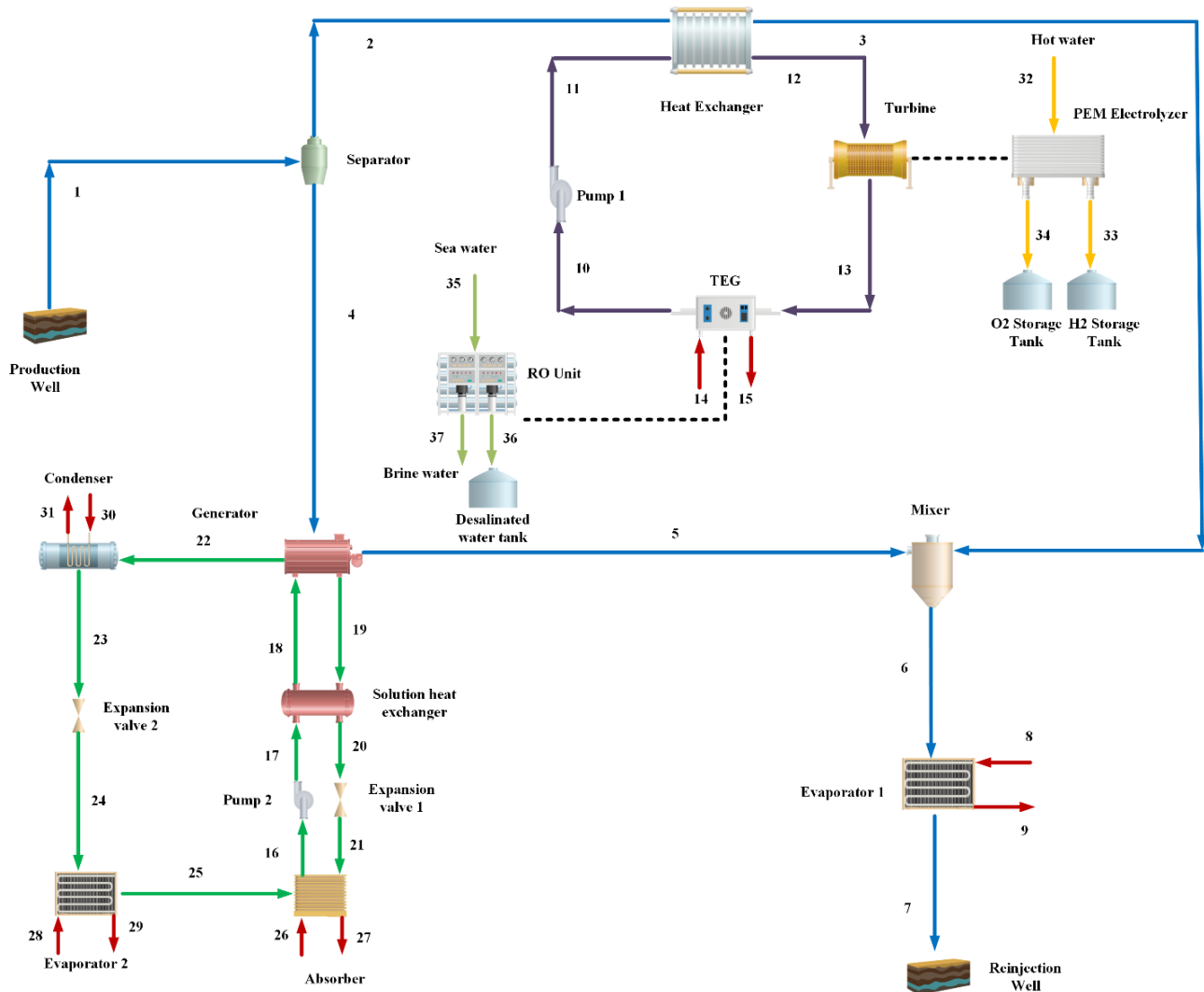


Fig. 1. The multigeneration system to produce power, heating, hydrogen, cooling and freshwater.

The integration of these subsystems allows the system to work effectively without additional energy inputs. The system achieves exergy minimization and overall efficiency maximization by utilizing sequential energy distribution – from high-grade energy to electricity production to low-grade heat for residential and industrial use. This integrated approach is particularly suitable for remote settings or establishments with an intense energy requirement (hospitals, campus, or industrial complexes) where energy need is critically essential.

2.2 Reservoir sustainability considerations

To carry out the calculations regarding the present research, it is considered that the targeted geothermal reservoir holds constant thermal and chemical properties throughout its functioning period. Constant reinjection can however create the long-term dynamics of the resource in the actual systems. Heat flooding occurs whenever the extraction rate exceeds the natural rate of replenishment of a reservoir, and frequent re-

moval of the heat causes the average temperature of the reservoir to decrease as a result of continually removing energy, an effect called thermal breakthrough, especially where the production and water injection wells are well spaced. At the same time, temporal and spatial changes of brine chemistry could be possible during circulation due to fluid mixing, enabling mineral precipitation and ultimately mineral-rock interactions that could potentially reduce permeability and subsequently lower the heat-recovery efficiency with time. Even though these are thermo-hydro-chemical processes beyond the analysis as of now, their effects on the sustainability of the reservoir are noted and recognized. A fish-bowl scale appraisal would thus demand integration of reservoir-scale thermal, hydraulic, and chemical modelling to explore long-term effects and to plan and schedule optimal reinjection schemes.

2.3 The initial assumptions

The proposed geothermal-energy system has special assumptions needed to conduct an analytical feasibility and performance accuracy. The arrangement is at steady-state conditions thus making transient analysis unnecessary. Loss of heat sources due to heat exchangers, pipelines, and storage tanks are assumed small and relatively insignificant to a whole energy transfer. In the case of the Organic Rankine Cycle (ORC), superheated R123 vapor: used to drive the turbine is condensed to a saturated temperature thus creating a saturated liquid. The absorption chiller uses lithium bromide (LiBr) and Water (H₂O) as the absorb and refrigerated component, respectively. Values of Turbine, pump and Thermoelectric Generator (TEG) efficiencies are extracted out of established literature material. The turbine and the pump are taken as isentropic, whereas it is supposed that the TEG works with a fixed efficiency to transform waste heat into electrical power. Such pressure drops in heat exchangers, pipes and valves are ignored but this may not be the case when significant pressure differences occur in a particular component. Among other assumptions, the geothermal streams after separation are assumed to perfectly recombine, without losses of energy due to incomplete mixing. The thermophysical properties of geothermal fluid that will flow out of the separator are assumed constant and to be in a single-phase liquid/saturated state or remain unchanged at the observed temperature. Exergy is done using a reference condition of 25 degrees Celsius and 1 atm. The Proton Exchange Membrane (PEM) electrolysis cell is simulated in ideal conditions of electrolysis and the Reverse Osmosis (RO) unit is assumed to be worked in ideal conditions of membrane with ideal recovery and con-

stant brine rejection rate. Expansion of the ORC and absorption chiller are defined based on the isenthalpically model of expansion in which exergy loss is taken into consideration devoid of heat and work interactions.

This given study is based on a series of standard assumptions, i.e. heat and pressure losses are considered to be insignificant, ideal efficiency of the components, and unchanged thermophysical properties, which are commonly used in the theoretical analysis of energy systems. The idealizations allow a strict examination of the thermodynamic and exergetic potential of the geothermal cycle in question. Minor losses related to heat exchangers, the pipes and the tanks involving the storage of liquids and ignoring the effects of the turbines and the pumps, as isentropic, allows the study to focus on the basic thermodynamic performance of the cycle. Such assumptions, however, do not hold well in real life circumstances. Real systems face a lot of operational barriers and ineffectiveness. The temperature and pressure fall in heat exchangers, pipes and storage tanks suggest the actual energy losses that are degrading the overall efficiency. The degradation effect, which can be a physical as well as a chemical effect, as well as material limitation, and the dynamic variation of operating conditions also affects the performance of Proton Exchange Membrane (PEM) electrolyzer and Reverse Osmosis (RO) unit. Besides, natural geothermal sources are known to have temporal variations which can cause deviations of the steady-state conditions made here. Correspondently, the highly idealization model utilized in this discussion should be understood as a conceptual reference as the reference of what should actually be possible in reality, but not a true commitment of the end outcome levels of performance.

2.4 Thermodynamic equations

Using Equations (1) to (5), together with the corresponding control volume, the mass balance, energy balance, and exergy balance for various cycle components can be established [21–23].

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}, \quad (1)$$

$$\sum_{in} \dot{m}_{in} h_{in} + \dot{Q} = \sum_{out} \dot{m}_{out} h_{out} + \dot{W}, \quad (2)$$

$$\dot{Ex}_Q + \sum_{in} \dot{m}_{in} ex_{in} = \sum_{out} \dot{m}_{out} ex_{out} + \dot{Ex}_W, \quad (3)$$

$$\dot{Ex}_Q = \left(1 - \frac{T_0}{T_i}\right) \dot{Q}_i, \quad (4)$$

$$\dot{Ex}_W = \dot{W}. \quad (5)$$

The work completed by each of the system components is indicated by $\dot{W}$, $\dot{Q}$ denotes the heat taken or

released by the system, h denotes specific enthalpy and m denotes the mass of the fluid entering or leaving.

As seen from Equations (6) to (10), each of the lines stated in Figure 1 can have its rates of exergy calculated independently:

$$\dot{E}x = \dot{m} ex, \quad (6)$$

$$ex = ex_{ph} + ex_{ch}, \quad (7)$$

$$\dot{E}x_{ph} = \sum \dot{m} [(h - h_0) - T_0(s - s_0)], \quad (8)$$

$$\dot{E}x_{ch} = \dot{m} ex_{mix}^{ch}, \quad (9)$$

$$\dot{E}x_{mix}^{ch} = \left[\sum_{i=1}^n X_i ex_i^{ch} + RT_0 \sum_{k=1}^n X_k \ln X_k \right]. \quad (10)$$

2.5 Exergoeconomic

A well-based operation of the system depends on the use of exergoeconomic method. The foundation of this methodology is based on thermodynamic and exergy assessment. Exergo-economical calculations are done for each system on the components cost basis [24]. The conversion of capital investment cost into a unit-time cost is possible from the use of equation below.

$$\dot{Z}_k = \frac{Z_k \varphi \text{CRF}}{3600 N}. \quad (11)$$

Z_k represents the equipment amounts in dollars. The method for calculating the capital recovery factor (CRF), is shown below. The capital recovery factor depends both on the estimate interest rate and the life of the equipment [24].

$$\text{CRF} = \frac{i_r(1 + i_r)^n}{(1 + i_r)^n - 1}, \quad (12)$$

i represents the interest rate and n indicates the total number of system operations. In this expression, N will represent annual hours' unit operation (7446), whereas φ is the maintenance factor which is at 1.06.

Thermoeconomic equations for component-level analysis given in Table 1 are a set of equations to calculate the costs from energy and conversion to exergy losses and capital need. The structured equation system simplifies allocation of costs, it supports the monitoring of both financial and thermal performance, and assists in identifying the components with highest contribution to costs that can be optimized.

Table 2 supplies both the mathematical formulations and pertinent auxiliary information needed to compute exergy flow costs and unit costs for each component. The approach offers full assessment of economic losses, delineates capital and operation costs, and also helps in adopting enablers for optimization, performance enhancement.

Table 1. Cost balance equations for individual system components derived from the thermoeconomic analysis [25–28]

Component	Function of purchase cost (\$)
Turbine	$Z_T = 4750 (\dot{W}_T)^{0.75}$
Heat exchanger	$Z_{HX} = 130 \left(\frac{A}{0.093} \right)^{0.78}$
Evaporator	$Z_{eva} = 1397 (A_{eva})^{0.89}$
Generator	$Z_{des} = 17500 (A_{gen})^{0.514}$
Pump	$Z_p = 1120 (\dot{W}_{pump})^{0.8}$
Condenser	$Z_{cond} = 1773 \dot{m}_{cond}$
Expansion valve	$Z_{exv} = 114.5 \dot{m}_{exv}$
TEG	$Z_{TEG} = 1500 (\dot{W}_{TEG})$
PEM	$Z_{PEM} = 1000 (\dot{W}_{PEM})$
RO	$Z_{RO} = n_e n_p c_k + n_p c_p + 996 (\dot{m}_{36})^{0.8}$

Table 2. Cost balance and auxiliary equations used for the thermoeconomic evaluation of the components within the studied system.

Components	Cost balance equation	Auxiliary equation
Separator	$\dot{C}_1 = \dot{C}_2 + \dot{C}_4$	$c_2 = c_4$
Heat exchanger	$\dot{C}_2 + \dot{C}_{11} + \dot{Z}_{HX} = \dot{C}_3 + \dot{C}_{12}$	$c_2 = c_3$
Turbine	$\dot{C}_{12} + \dot{Z}_T = \dot{C}_{13} + \dot{C}_{w,T}$	$c_{12} = c_{13}$
TEG	$\dot{C}_{13} + \dot{C}_{14} + \dot{Z}_{TEG} = \dot{C}_{10} + \dot{C}_{15}$	$c_{13} = c_{10}, c_{14} = 0$
Pump 1	$\dot{C}_{11} = \dot{Z}_{pump1} + \dot{C}_{10} + \dot{C}_{w,pump1}$	$c_{w,pump1} = c_{w,T}$
Mixer	$\dot{C}_3 + \dot{C}_5 = \dot{C}_6$	$c_3 = c_5$
Evaporator 1	$\dot{C}_6 + \dot{C}_8 + \dot{Z}_{eva1} = \dot{C}_7 + \dot{C}_9$	$c_6 = c_7, c_8 = 0$
Generator	$\dot{C}_4 + \dot{C}_{18} + \dot{Z}_{gen} = \dot{C}_5 + \dot{C}_{19} + \dot{C}_{22}$	$c_4 = c_5, \frac{\dot{C}_{19} - \dot{C}_{18}}{\dot{E}x_{19} - \dot{E}x_{18}} = \frac{\dot{C}_{22} - \dot{C}_{18}}{\dot{E}x_{22} - \dot{E}x_{18}}$
Condenser	$\dot{C}_{22} + \dot{C}_{30} + \dot{Z}_{cond} = \dot{C}_{23} + \dot{C}_{31}$	$c_{22} = c_{23}, c_{30} = 0$
SHX	$\dot{C}_{17} + \dot{C}_{19} + \dot{Z}_{SHX} = \dot{C}_{18} + \dot{C}_{20}$	$c_{19} = c_{20}$
Pump 2	$\dot{C}_{17} = \dot{Z}_{pump2} + \dot{C}_{16} + \dot{C}_{w,pump2}$	$c_{w,pump2} = c_{w,T}$
Evaporator 2	$\dot{C}_{24} + \dot{C}_{28} + \dot{Z}_{eva2} = \dot{C}_{25} + \dot{C}_{29}$	$c_{24} = c_{25}, c_{28} = 0$
Absorber	$\dot{C}_{25} + \dot{C}_{21} + \dot{C}_{26} + \dot{Z}_{abs} = \dot{C}_{16} + \dot{C}_{27}$	$c_{29} = 0, \frac{\dot{C}_{21} + \dot{C}_{25}}{\dot{E}x_{21} + \dot{E}x_{25}} = c_{16}$
PEM	$\dot{C}_{32} + \dot{C}_{w,PEM} + \dot{Z}_{PEM} = \dot{C}_{33} + \dot{C}_{34}$	$c_{w,PEM} = c_{w,T}, c_{34} = 0$
RO	$\dot{C}_{35} + \dot{Z}_{RO} + \dot{C}_{w,RO} = \dot{C}_{36} + \dot{C}_{37}$	$c_{w,RO} = c_{TEG}, c_{35} = c_{37} = 0$

2.6 Exergoeconomic

The equations required for exergoenvironmental analysis of the system under study are [29]:

The activity environment index relationship is shown below:

$$\varepsilon_{ei} = \frac{\dot{E}x_D}{\sum \dot{E}x_{in}} \quad (13)$$

The environmental damage effectiveness index is shown below:

$$\varepsilon_{ed} = \frac{\varepsilon_{ei}}{\eta_{ex}} \quad (14)$$

The exergy stability coefficient is calculated as follows:

$$\varepsilon = \frac{\dot{E}x_D}{\dot{E}x_{out} + \dot{E}x_D + 1} \quad (15)$$

3 Results and Discussion

The proposal for validation is looks at the consistency between simulation thereof and the existing studies. Three aspects are emphasized in the validation methodology, namely – Organic Rankine Cycle (ORC) and absorption chiller. Output metrics of these subsystems are compared to the results of the previously published studies and presented in tabular forms. The verification results show that the system performance for the main subsystems is in line with that established earlier in another research.

Table 3. Comparison of ORC Subsystem Performance with Previous Studies of Liu et al [30].

Parameter	Ref. [30]	Present Work	Deviation, %
Net Power Output (kW)	112	115	+2.68
Thermal Efficiency (%)	14.1	13.5	−4.26
Turbine Inlet Temperature (°C)	155	150	+3.23
Mass Flow Rate (kg/s)	0.78	0.8	+2.56

Table 4. Comparison of Absorption Chiller Performance with the Study of Ketfi & Boudghene Stambouli [31].

Parameter	Ref. [31]	Present Work	Deviation, %
Cooling Capacity (kW)	145	148	+2.07
COP	0.76	0.74	−2.63

Table 5 describes the performance of a proposed multigeneration system in which power generation,

heating, cooling, hydrogen manufacturing and fresh-water supply are integrated. The Organic Rankine Cycle turbine provides 229.8 kW of electricity, which is augmented by 17.08 kW of electricity from a Thermoelectric Generator for a total electricity supply of 246.88 kW. The system produces 8.4 kW heat and 12.12 kW cooling. The system shows significant performance with energy and exergy efficiencies of 66.42% and 77.12% respectively. It is estimated that 1570.44 kW of exergy is wasted in the form of system losses.

Table 5. Overall performance results for the multi-generation system

The amount of power produced by the ORC Turbine (kW)	229.8
The amount of power produced by the TEG (kW)	17.08
Total system produced work (kW)	246.88
The amount of heating produced by the Evaporator 1 (kW)	8.4
Overall energy efficiency (%)	66.42
Overall exergy efficiency (%)	77.12
Total exergy destruction of the system (kW)	1570.44
Production cooling rate (kW)	12.12
COP	0.68
Hydrogen production rate (kg/s)	0.001135
Freshwater production rate (kg/s)	0.525
Freshwater production rate (m ³ /h)	1.89
Freshwater production rate (m ³ /day)	45.4

The coefficient of performance (COP) of the multi-generation system under investigation reveals that it has a good value of 0.68, which represents satisfactory heat and cooling performance. This value of COP is slightly smaller than the 0.70-0.80 range of standalone single-effect LiBr–H₂O absorption chillers. Such deviation is expected because the chiller is powered with the heat that is already partially used in the ORC and TEG subsystems. This type of arrangement lowers the heating temperature but allows simultaneous generation of multiple energy and water outputs thus signifying an active trade-off between the performance of single components and system-level optimization. Besides, it generates 0.001135 kg/s hydrogen and 0.525 kg/s freshwater thus being one of the sweet candidates for integrated energy-water-hydrogen systems. In practical terms, the freshwater output of 0.525 kg/s works out to roughly 1.89 m³/h, or about 45.4 m³/day if the system runs continuously. Based on the available results, we can express the energy–water performance in two ways. First, the TEG-powered water intensity is about 9.0 kWh for every cubic meter of water produced, calculated from the TEG's electrical output of 17.08 kW and the water flow rate above. Second, the overall system co-

production intensity comes to around 130.6 kWh/m^3 when the total net electric output of 246.88 kW is used in the same way. This second figure is intended purely as a combined production indicator and should not be read as the RO unit's own electricity consumption. Determining that value would require a detailed breakdown of the RO subsystem's power use, which was beyond the present scope but is planned for future work. The water output itself could be increased by adding membrane area or diverting more of the system's thermal or electrical capacity to the RO stage.

Table 6 presents the exergoeconomic parameters of a geothermal-based multigeneration system. The geothermal resource, being cost-free and renewable, incurs thermodynamic inefficiencies during energy retrieval. The system's high exergoeconomic factor (97.09%) is mainly due to capital-related expenses, with the turbine having the highest factor (49.27%) because of significant investment and maintenance costs. Components like the condenser and heat exchangers (HX, SHX) have much lower exergoeconomic factors (1.45%, 1.28%, and 3.47%), indicating potential for improvement in performance and cost reduction. The PEM electrolyzer and reverse osmosis (RO) unit, with

factors around 7.7%, contribute to multigeneration functionality but also show room for economic improvement through thermal integration or new technologies. Optimizing components with low exergoeconomic factors and high exergy destruction rates will offer the greatest potential for performance and cost-effectiveness.

The value of 286,997 $\text{\$/year}$ means total annualized capital cost in the table translated to a capital recovery factor (CRF) of about 0.1019 when one considers a discount rate (i) of 8 percent interest; and a future life expectancy (n) of 20 years. This would in its turn point to a total installed CAPEX around USD 2.82 million. Sensitivity analysis of $i = 5\text{--}12\%$ and $n = 15\text{--}25$ years will provide a CAPEX of USD 2.46–3.58 million. Maintenance costs are also already accounted through the maintenance factor: 1.06; other peripheral costs (replacing components or auxiliary energy consumption costs) will be limited with the present configuration. Regarding scalability, technologically, the bigger systems are expected to reduce certain capital expenditure with economies of scale but smaller ones may have higher unit capital costs but better flexibility and portability to remote or site-specific use.

Table 6. Exergy Cost and Economic Indicators of System Units

Component	c_F ($\text{\$/GJ}$)	c_P ($\text{\$/GJ}$)	$\dot{C}_D$ ($\text{\$/year}$)	$\dot{Z}$ ($\text{\$/year}$)	f (%)
Geothermal	0	0.808	1000	33260	97.09
HX	0.8501	1.231	7437.1	96.628	1.282
Pump 1	1.852	2.638	63.51	44.282	12.23
Turbine	1.24	1.852	1154.3	1121.2	49.27
TEG	1.24	1.356	405.49	81.094	16.66
Generator	1.24	1.643	3128.1	168.79	5.11
Condenser	1.643	2.831	2021.1	29.922	1.45
Evaporator	2.688	5.275	1275.9	251.93	16.48
Absorber	1.643	2.808	2155.4	145.87	6.33
SHX	0.865	1.643	632.45	22.76	3.47
PEM	1.24	6.26	698.36	58.2	7.7
RO	2.16	4.8	502.5	41.8	7.68
Total	-	-	-	286997	-

Note: Estimated total CAPEX ($i = 8\%$, $n = 20$ years; $\text{CRF} \approx 0.1019$): USD 2.82 million. CAPEX range for $i = 5\text{--}12\%$ and $n = 15\text{--}25$ years: USD 2.46–3.58 million.

As illustrated in Figure 2, the graphic shows how $\dot{Z}_D + \dot{C}_D$ throughout system elements is an indication of the summation of financial and thermodynamic burdens associated with annual capital outlay and exergy loss. Expenditure incurred during the years in the geothermal unit is $\$34,260$ which is more than that spent on Heat Exchanger (HX) namely, $\$7,533.70$, Generator, which is $\$3,296.89$ and the Absorber $\$2,301.27$. These components are the major source of economic

spending in the system drawing most of its expenditure from robust capital spending and increased exergy destruction. Management of components with increased $\dot{Z}_D + \dot{C}_D$ values is strategic for improving resource use and system efficiency, hence simultaneous money saving and energy saving. Improvement of key system elements is essential for cutting costs and increasing energy saving in energy-based systems.

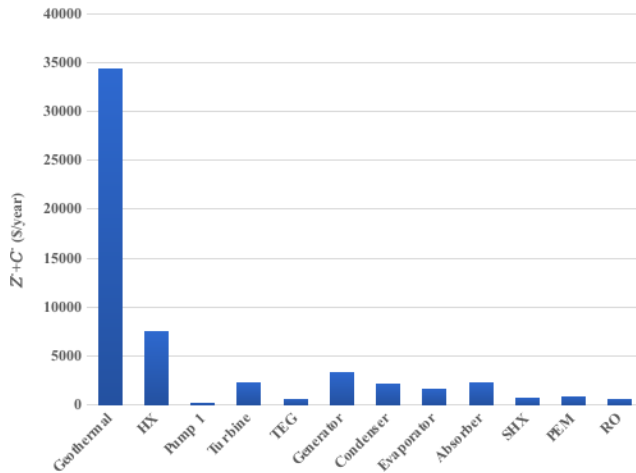


Fig. 2. Annual economic exergy cost $\dot{Z}_D + \dot{C}_D$ for system components, highlighting the most significant contributors to total system costs.

How exergy is destroyed in a multigeneration system based on geothermal is systematically evaluated in Figure 3. Inside the general picture, the geothermal subsystem presents the largest source of exergy loss that contributes a percentage of about 83% of the total exergy destruction. In addition, the major heat exchanger (HX) is considered a source of 28% of the exergy loss. Unless these two aspects are mitigated, their combination produces an estimated three quarters of the overall system-level exergy destruction. The Organic Rankine Cycle turbine and generator run with normal conditions and present only slight exergy losses. The thermoelectric generator (TEG) has also other irreversibilities, and the ancillary equipment- pumps, absorbers, and secondary heat exchangers- contributes insignificant exergy destruction. This means that the main focus must be on minimizing the irreversibilities that occur due to the geothermal extraction machinery, and the heat-exchange mechanisms.

A number of intervention measures are suggested to help contain the found to be huge exergy losses. Minimal thermal losses would be achieved through the optimization of heat extraction techniques applied to the geothermal resource via augmented fluid extraction technology and implementation of the complex heat-exchange schemes. Greater heat exchange would be achieved with use of counterflow heat exchangers, or more efficiently designed heat exchangers like plate-and-frame or in-line tube-and-tube heat exchangers would close temperature differential, and destroy less exergy. In complementary fashion, the possibility of adaptive control strategies would modify the system behavior on-the-fly to changes in heat flow, thus removing any inefficiencies potentially brought about through a mismatching of thermodynamic requirements. When these measures are combined, they should significantly

reduce the destruction of exergy in both the geothermal subsystem and in the heat exchangers, which increase the efficiency and sustainability of the multi-generation system overall.

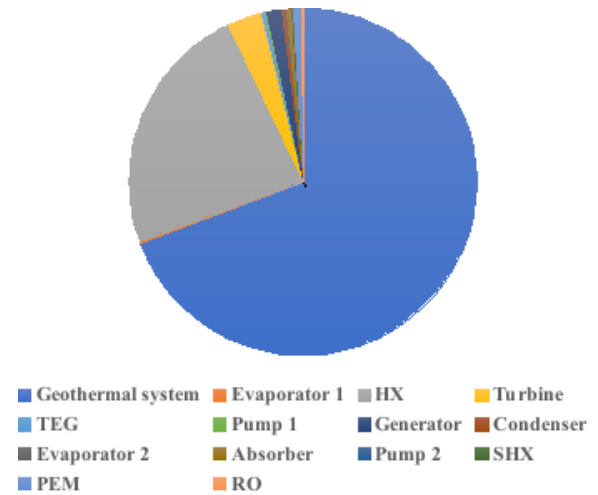


Fig. 3. Exergy destruction rate for different components of the system.

Environmental exergy analysis outputs for the geothermal-based multigeneration system, as found in Table 7, are evaluated using three major parameters to ascertain environmental effect. the Activity Environment Index (ε_{ei}), Environmental Damage Effectiveness Index (ε_{ed}), and Exergy Sustainability Coefficient (ε_{es}).

Activity Environment Index (ε_{ei}): However, at the level of 0.03206 this index indicates a low environmental interaction of the system, as a result leading to minor negative mechanisms on the ecosystem.

Environmental Damage Effectiveness Index (ε_{ed}): The value of 0.037 that characterizes moderate environmental impact indicates that although system is efficient, inefficiencies cause high environmental burdens.

Exergy Sustainability Coefficient (ε_{es}): The value of 0.0711 stands for the fact that the degree of sustainability is achieved, while further improvements as it concerns exergetic conservation and environmental performance are possible.

Table 7. Exergy environmental parameters of the system.

ε_{ei}	0.03206
ε_{es}	0.0711
ε_{ed}	0.037

Despite having good sustainability performance, minimal environmental impact, the system brings good opportunities for further improvements. Raising energy-efficiency and reducing exergy loss through heat exchangers as well as geothermal extraction units will

contribute to the overall performance and sustainability of the systems.

Figure 4 shows that as current is raised in a PEM electrolyzer energy and exergy efficiencies decrease. In particular, between 1,000 and 10,000 A/m², the global energy efficiency decreases by a mean of about 66.5% down to 60.8% whereas exergy efficiency decreases by a mean of about 62.1% down to 56.9%. The phenomenon can be easily explained based on the fact that activation and ohmic losses increase with increasing current density, therefore, increasing part of supplied power is wasted as heat, instead of being spent on hydrogen production. These findings outline a typical trade-off between efficiency of production of hydrogen and speed. Most steady-state applications should operate in the mid-current operating range of 3000–4000 A/m, where success was determined to be serviceable efficiency and sufficient current density to achieve reasonable life-cycle goals. However, conditions might demand higher current densities – as when geothermal power is overproduced, or there is slackness in other parts of the system – and energy conservations may justify current reduction at times to restrict the production of power and hence the electrolyzer availability to other system uses.

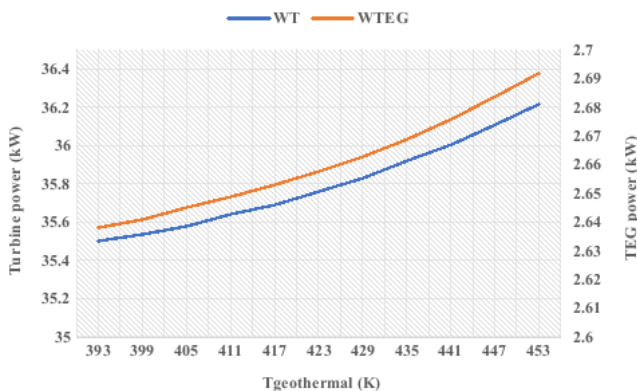


Fig. 4. The effect of current density on the efficiency of the PEM electrolyzer.

Figure 5 demonstrates the relationship between geothermal fluid temperature and power output for the Organic Rankine Cycle (ORC) turbine (WT) and Thermoelectric Generator (TEG) (WTEG). As geothermal heat increases from 393 K to 453 K, the ORC turbine's power output rises from 35.5 kW to 36.22 kW due to greater enthalpy differences and optimized expansion cycles. This results in improved electric energy production. Meanwhile, the TEG output increases from 2.638 kW to 2.692 kW, as higher geothermal temperatures boost turbine exhaust thermal energy, which the TEG converts into additional electricity using the Seebeck effect. This combined

ORC-TEG system enhances overall performance, eliminates the need for cooling systems, and is ideal for off-grid or water-scarce locations, as it generates extra power without additional resource consumption.

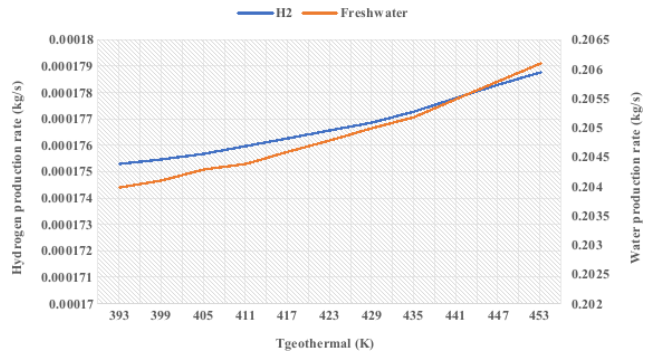


Fig. 5. The effect of geothermal temperature on the amount of power produced in turbine and TEG.

As illustrated in Figure 6, the graph shows the relationship between geothermal fluid temperature and hydrogen generation efficiency and freshwater generation efficiency in the integrated renewable energy system. The increase in the temperature of geothermal 393 K to 453 K results in a minute increase in hydrogen production with the final increase from 0.0001753 kg/s to 0.0001788 kg/s due to the enhanced ORC turbine performance. Greater production from the PEM electrolyzer leads to higher hydrogen yield. With TEG system drawing turbine exhaust heat to utilize in the Reverse Osmosis (RO) desalination unit, freshwater production increases by a small value from 0.204 kg/s to 0.2061 kg/s. By increasing electrical production of TEG, it helps to propel the RO unit and allow waste heat to be converted to clean drinking water.

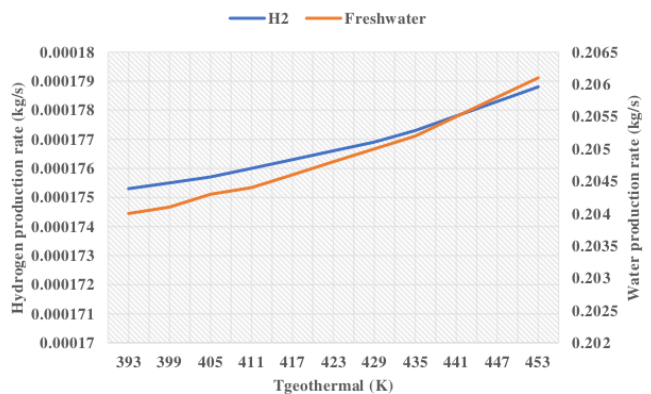


Fig. 6. The effect of geothermal temperature on the amount of hydrogen and freshwater

4 Conclusion

The overall examination of a geothermal multigeneration system was performed by evaluating it in terms of meeting the 4E (Energy, Exergy, Economic, Environmental) criteria to reveal its efficiency in terms of generating multiple outputs. The comparative examinations were used to show its validity since there were minimal variations as compared to those in the earlier researches and hence showed its reliability and accuracy. The setting proved to hold a lot of promise in producing electricity being able to turn its geothermal force into 229.8 kW via an Organic Rankine Cycle (ORC) turbine. Additional 17.08 kW was generated by attaching Thermoelectric Generator (TEG) to retrieve the leftover heat of the turbine exhaust further improving the total output to make 246.88 kW. The finding proves the worth of the TEG in not only augmenting the overall energy recovery but also the decreasing dependence on prevailing cooling gadgets.

It also released 8.4 kW of heat and 12.12 kW of chilling and a Single-Effect Absorption Chiller (SEAC) was efficient in producing cooling with the assistance of geothermal heat. The fact that it can provide heating and cooling makes the system especially appropriate in case of hospitals facilities and industrial complexes where stable climate control is necessary. On balance, the system achieved an energy efficiency of 66.42%, and an exergy efficiency of 77.12%. Nevertheless, exergy destructions of 1570.44 kW were primarily realized under the geothermal resource source and the heat exchangers, hence pointing towards opportunities that could be enhanced to reduce such inefficiencies.

The demonstration system being investigated had the ability to produce both power and hydrogen as well as desalinated water through the simultaneous use of a geothermal brine flash unit, a proton exchange membrane (PEM) electrolyzer, a reverse osmosis (RO) water desalination unit, and a thermal energy storage tank. The clean hydrogen was generated and electricity produced in simultaneous conditions at steady-state operating conditions reaching production rates of 0.001135 kg/s hydrogen and 0.525 kg/s desalination. The energy conversion performance of the system was realized at 0.68, as the coefficient of performance (COP) of the heating and cooling operating loops. The number is acceptable comparing to the multigenerational design of the system according to which high-grade energy is reduced to low-grade energy forms.

Exergoeconomic analysis revealed that capital costs played the major role in the overall system expenditure. The most significant factor involved the acquisition of equipment and routine maintenance taken up

by 49.27% and 34.16%, respectively. The cost allocations also described the turbine, and the thermoelectric generator (TEG) the parts integrated with the energy storage system as the cost-critical parts of this model. Efforts to improve optimization could then be made on these elements with the aim of decreasing overall expenses.

The environmental impact was measured through the Activity Environmental Index (AI) and has produced the value of 0.03206 that represents a slight environmental disturbance. There was an environmentally beneficial performance of the overall system with a value of the Environmental Damage Effectiveness Index (IDE) of 0.037 and an Exergy Sustainability Coefficient (ECC) value of 0.0711, despite exergy losses in the geothermal extraction process, as well as, in the heat-exchange process being considered as significant.

The term minimal direct ecological disturbance refers to the localized spatial extent of the physical footprint of a system (land use; direct emissions; atmospheric sound production). Despite the total exergy annihilation of 1,570.44 kW in the system, such amount is the result of internal loss of energy-quality in conversion processes, but not thermodynamic irreversibilities. In turn, scaling ecological level to a loss of exergy is improper. The outputs of the system, however, hold potential in reducing environmental impact: the production of hydrogen can replace fossil-based hydrogen, therefore removing the necessary CO₂ emissions, and freshwater can reduce dependence on the more energy-consuming or fossil-powered desalination systems.

In the current study, 4E framework is used to identify four key optimization opportunities that include; (1) reducing degradation of exergy due to improved heat recovery and optimization of heat-exchanger networks; (2) coupling the thermoelectric generator (TEG) with the turbine to increase net electricity production; (3) optimizing coupling between the proton-exchange membrane (PEM) electrolyzer and reverse osmosis (RO) unit to decrease the specific energy requirement and (4) integrating advanced control strategies to dynamically allocate resources. A comprehensive approach that seeks to apply these measures together provides a complete route towards efficiency, low operating expenses and improved environmental compliance.

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