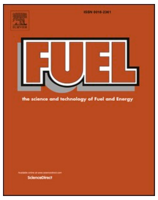
Fuel 359 (2024) 130430

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel



Full Length Article

Development of models for green hydrogen production of Turkey geothermal Resources: A case study demonstration of thermodynamics and thermoeconomics analyses

Muhammed Arslan [a], Ceyhun Yilmaz [b,*]

[a] Afyon Kocatepe University, Motor Vehicles and Transportation Technologies Department, Afyonkarahisar, Turkey
[b] Afyon Kocatepe University, Mechanical Engineering Department, Afyonkarahisar, Turkey

ARTICLE INFO

Keywords:
Geothermal energy
Hydrogen production
Thermodynamic
Thermoeconomic

ABSTRACT

The transition to sustainable and clean energy sources has become imperative in the face of global climate change concerns. Hydrogen is a versatile and environmentally friendly energy carrier among the potential solutions. Utilizing renewable resources for hydrogen production is a promising avenue, and Turkey's geothermal resources offer significant potential. This study focuses on developing models for assessing Turkey's geothermal resources' green hydrogen production potential, employing thermodynamics and thermoeconomics analyses. The thermodynamic analysis explores the thermophysical properties of geothermal fluids, investigating the feasibility of utilizing the available heat for hydrogen production through electrolysis. As a result of the performance analysis, the Afyon Geothermal Power Plant (AFJES) produces 4132 kW net power with 150 kg/s geofluid at 110°C. The unit costs of the electricity and hydrogen produced in the power plant are 0.01671 \$/kWh and 1.684 \$/kg, respectively. The study aims to determine the optimal conditions and configurations for efficient hydrogen production from Turkey's geothermal resources. The findings provide valuable insights for policymakers, investors, and energy stakeholders, aiding in the decision-making process for deploying sustainable and economically viable hydrogen production in Turkey's geothermal-rich regions. Furthermore, this research contributes to the broader objective of achieving a low-carbon energy future while tapping into the immense potential of geothermal resources.

1. Introduction

There has been an increasing global focus on transitioning to sustainable and environmentally friendly energy sources in recent years. The search for alternative energy solutions has intensified as the world grapples with the challenges posed by climate change and the need to reduce greenhouse gas emissions. In this context, hydrogen has emerged as a promising option because it can serve as a clean and versatile energy carrier. One of the most sustainable methods for producing hydrogen is using renewable resources, such as geothermal energy. Turkey, situated in a geologically active region, is endowed with significant geothermal resources that have the potential to contribute to the country's energy transition. Geothermal energy offers several advantages, including its abundance, reliability, and minimal greenhouse gas emissions. As a result, there is growing interest in exploring the feasibility of utilizing Turkey's geothermal resources to produce green hydrogen [1].

This study focuses on developing models for assessing Turkey's geothermal resources' green hydrogen production potential. The analysis incorporates both thermodynamic and thermoeconomic considerations to provide a comprehensive understanding of the feasibility and viability of this renewable energy pathway. By examining the thermodynamic properties of geothermal resources and applying economic analysis, this research aims to determine the optimal conditions and configurations for efficient hydrogen production [2]. The thermodynamic analysis delves into the thermophysical properties of geothermal fluids. It investigates the potential for harnessing the available heat to generate hydrogen through the electrolysis processes. Additionally, the study evaluates the integration of hydrogen production with power generation, aiming to maximize the geothermal system's overall efficiency and energy utilization [3].

Furthermore, the thermoeconomic analysis explores the economic viability of green hydrogen production from geothermal resources. It considers factors such as capital costs, operational expenses, and market

---

* Corresponding author.
E-mail address: ceyhunyilmaz@aku.edu.tr (C. Yilmaz).

https://doi.org/10.1016/j.fuel.2023.130430
Received 15 September 2023; Received in revised form 5 November 2023; Accepted 15 November 2023

Nomenclature

Symbols

c	Specific unit cost (\$/GJ)
C_k	Purchased equipment cost (\$)
C	Cost rate associated with exergy (\$/h)
CRF	Capital recovery factor
EES	Engineering Equation Solver
ex	Specific exergy (kJ/kg)
$\dot{E}x$	Exergy flow rate (kW)
h	Specific enthalpy (kJ/kg)
i	Interest rate
kt	Kilotons
$\dot{m}$	Mass flow rate (kg/s)
ORC	Organic Rankine Cycle
P	Pressure (kPa)
PEMFC	Proton Exchange Membrane Fuel Cell
s	Specific entropy (kJ/kgK)
T	Temperature (K or ℃)
$\dot{W}$	Power (kW)
$\dot{Z}_k$	Total cost rate (\$/s)

Subscripts

e	Exit stream
i	Inlet stream
o	Dead state

Greek Symbols

η_{th}	Energy Efficiency (%)
η_{ex}	Exergy Efficiency (%)
\$	United State Dollars
φ	Operating and maintenance cost ratio

prices to assess the financial feasibility and competitiveness of the proposed hydrogen production models. Considering the economic aspects alongside the thermodynamic analysis, this study aims to provide insights into the economic viability and potential profitability of green hydrogen production from Turkey's geothermal resources [4]. The findings of this research can have significant implications for Turkey's energy sector and contribute to its sustainable development goals. Understanding geothermal resources' green hydrogen production potential can inform policymakers, investors, and energy stakeholders in their decision-making processes, paving the way for deploying innovative and sustainable energy solutions. Additionally, the results of this case study can provide valuable insights for other countries with similar geothermal resources, facilitating the adoption of green hydrogen production as a critical driver of their energy transition. Some relevant studies of geothermal low-temperature sources' usage of hydrogen production in the literature are summarized below.

Cao et al. [5] have optimized an ORC, which operates with geothermal energy and is combined with PEMFC, thermodynamically and thermoeconomically. In the optimization process, geothermal water temperature and ORC high pressure have been assessed on critical parameters. As a result of optimization, when energy efficiency and hydrogen production can be increased by 2——3 points and 35 % − 41 %, respectively, the unit cost of hydrogen exergy can be decreased by 9.5 % − 12 %.

The following literature studies are on geothermal energy multigeneration systems. Cao et al. [6] modeled thermodynamically an integrated energy system consisting of a multi-effect desalination system, geothermal energy system, and hydrogen production and investigated system performance. The parameters like ORC net power and hydrogen produced in the electrolyzer were studied multi-dimensionally with EES and Matlab. According to conclusions, the central geothermal temperature is important for system exergy efficiency and cost. Li et al. [7] aimed to develop a trigeneration system based on a transcritical CO2 cycle for producing hydrogen, power, and freshwater with geothermal-solar energies. In conclusion, the maximum power, hydrogen, and freshwater produced were 1286 kW, 1.989 kg/h, and 13.38 m3/day, respectively, for May. In this case, the optimized system showed a performance of 17.07 \$/GJ unit product cost and 23.35 % energy efficiency. Li et al. [8] investigated five stages of heat recovery of a multigeneration system based on a flash-binary geothermal system to enhance the system's feasibility. They performed a sensitivity analysis based on energy, exergy, and exergoeconomic analyses. Conclusions have shown that the multigeneration system can produce 782 kW of electricity, 881.6 kW of cooling, 0.286 kg/s fresh water, and 0.181 kg/h hydrogen, respectively. Exergy efficiency and total unit product cost are 46.44 % and 3.98 \$/GJ, respectively. Sohani et al. [9] have optimized a multigeneration system driven by a solar-geothermal system using a dynamic multi-objective optimization method instead of a static multi-objective optimization method. As a result of optimization, it has been seen that the energy efficiency, exergy efficiency, and annual production of electricity, heating, fresh water, and hydrogen are 5.2 %, 3 %, 14.4 %, 16.1 %, 14.3 %, and 13.5 % more with dynamic method than static method, respectively. Regarding thermoeconomic, payback time can also be decreased from 5.56 to 4.43 years with a 4.4 % reduction of hydrogen storage pressure. Manesh et al. [10] have presented a multigeneration system driven by natural gas-geothermal-solar energies and performed energy, exergy, and exergoeconomic analyses. In analyses, 9 different working fluids have been used, and the best one has been picked. According to conclusions, the best energy efficiency, exergy efficiency, total annual cost, and hydrogen production are 23.87 %, 28.21 %, 0.144 \$/kWh, and 1.85 kg/h with R141b ORC working fluid, respectively. Xing and Li [11] have recommended a multigeneration system producing hydrogen with geothermal and biomass energies and have assessed with energy, exergy, and exergoeconomic analysis. In conclusion, the system has 22.23 MW net power, 34.13 MW heating effect, 96.4 MW cooling effect, and 124 kg/h hydrogen production. Also, the system's energy efficiency, exergy efficiency, and total product cost rate are 79.47 %, 17.87 %, and 1.162 \$/s, respectively. Alirahmi et al. [12] have proposed a multigeneration system producing electricity, oxygen, cooling, and hydrogen from geothermal energy and have assessed it with thermodynamic and thermoeconomic analysis. The system has been modeled by EES and optimized by NSGA-II multidimensionally. According to conclusions, the system has 4.696 MWh electricity, 37.85 % exergy efficiency, and a 15.09 \$/h system cost rate.

Finally, the following literature studies are on geothermal energy resources and the green hydrogen production potential of Turkey. Karayel et al. [13] investigated Turkey's geothermal energy potential for green hydrogen production. According to the research results, Turkey's total hydrogen production potential using alkaline and high-temperature solid-oxide electrolyzers is 559.76 kt. In addition, among Turkey's seven geographical regions, the Aegean Region has the highest hydrogen production potential. The study also stated that other regions can access underground heat, but more is needed to generate electricity. Yılmaz [14] modeled a geothermal power plant consisting of a Rankine cycle, steam cycle, desalination unit, and proton exchange membrane electrolyzer and performed thermodynamic, thermoeconomic, and environmental impact analysis. According to the analysis results, the power plant has a total power capacity of 1639 kW, a hydrogen production rate of 7.4916 kg/h, a hot water production rate of 49.18 k/h, a freshwater production rate of 11.38 kg/h, an energy efficiency of 52.01 % and exergy efficiency of 29.45 %, respectively. The total cost rate of the power plant was calculated as 139.6 \$/h, and the power plant prevented 5441 kg/h CO2 emissions. Atiz et al. [15] investigated the power and hydrogen production performance of an integrated system operating under Turkey conditions consisting of an ORC, solar panels, middle-temperature geothermal energy source, cooling tower, and proton exchange membrane electrolyzer. According to the research results, the power plant with 0.4 kg/s n-butane has a hydrogen production rate of 9.8071 kg/day, 5.85 % energy efficiency, and 8.27 % exergy efficiency, respectively.

1.1. *Turkey geothermal resources potential and fields geography*

As it is known, geothermal energy is a domestic underground resource that is renewable, clean, cheap, and environmentally friendly. Turkey is located on an active tectonic belt due to its geological and geographical location, so it is in a prosperous position among the world countries regarding geothermal. There are geothermal resources at different temperatures in the form of approximately 1000 natural outflows spread throughout Turkey. Turkey is the 1st country in Europe regarding geothermal potential and the 4th country in the world regarding installed power. The top five countries in electricity generation from geothermal energy are the USA, Indonesia, Philippines, Turkey, and New Zealand. The map showing the distribution of geothermal resources in our country is given in Fig. 1 [16].

The region with high-temperature sources is on the Büyük Menderes Graben in Western Anatolia. Starting from Pamukkale, Turkey's oldest geothermal power plant, Kızıldere is approximately 25 km west, then Salavatlı, approximately 66 km west of Kızıldere, and ends in Germencik, approximately 40 km west of Salavatlı. Fig. 2 shows Turkey's general tectonic and volcanic features and important geothermal fields [18].

The prominent graben lies between two parallel horsts in an alternating pattern of subsidence and uplift. To date, high-temperature geofluids have only been found in wells drilled on slip-step faults forming the northern boundary of the graben. These faults appear to be the primary fluid control structures along the entire east–west extension of the Graben from Germencik to Kızıldere in Fig. 3 [18].

Fig. 4 shows the cross-section of the area where the Kızıldere power plant and the hot spring Tekke Hamam are located, a few kilometers apart on both sides of the Menderes River. Hot springs are found on the Graben's north and south sides. The basement rock is gneiss, and the lithology of the reservoir consists of many layers belonging to various formations [19].

1.2. *Electricity generation from geothermal energy in Turkey*

The geothermal potential of Turkey is relatively high, and 78 % of the potential areas are in Western Anatolia, 9 % in Central Anatolia, 7 % in the Marmara Region, 5 % in Eastern Anatolia, and 1 % in other regions. 90 % of Turkey's geothermal resources are at low and medium temperatures and are suitable for direct applications (heating, thermal tourism, various industrial applications) and 10 % for indirect applications (electric power generation). The first electricity generation in geothermal energy applications was started in 1975 with the Kızıldere Power Plant with a power of 0.5 MWe. Fig. 5 shows the Turkey-geothermal power plants map. The geothermal energy installed power, widely used in electricity generation and district heating, is 1686 MW as of the end of June 2022. Its ratio in the total installed power is 1.66 %, and the change in installed power over the years and its ratio in the total installed power are given in the charts below. The total number of registered geothermal power plants in Turkey is 63. Also, the total installed power (MW) of geothermal power plants in Turkey is shown in Fig. 6 [20,21]. Karayel et al. [13] investigated the geothermal energy potential of Turkey for green energy production. The study was carried out to serve as a good base for planning and strategizing purposes as required for the country and help in developing new energy policies for exploiting renewable energy resources. According to the study's conclusions, Turkey has a significant green energy production potential. Especially, Aydın and Manisa have the highest green hydrogen production potentials, with a total hydrogen production potential of 175.51 and 103.30 kilotons, respectively.

Turkey has about 1000 known hot and mineral water sources and geothermal wells. The number of geothermal fields with temperatures above 40 °C is 170. 11 are high-temperature fields suitable for conventional electricity generation. The first geothermal power plant in

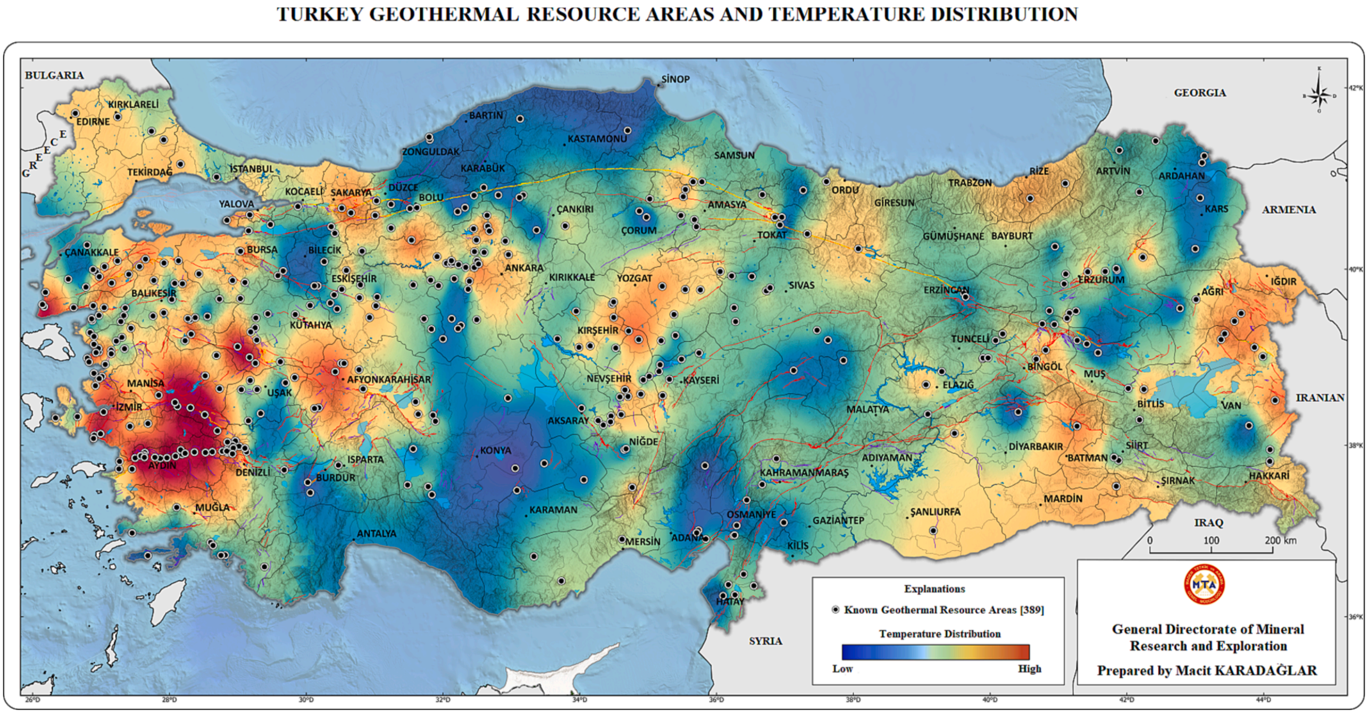


Fig. 1. Map showing the distribution of geothermal resources in Turkey [17].

Fig. 2. General tectonic, volcanic features and important geothermal fields of Turkey [18].

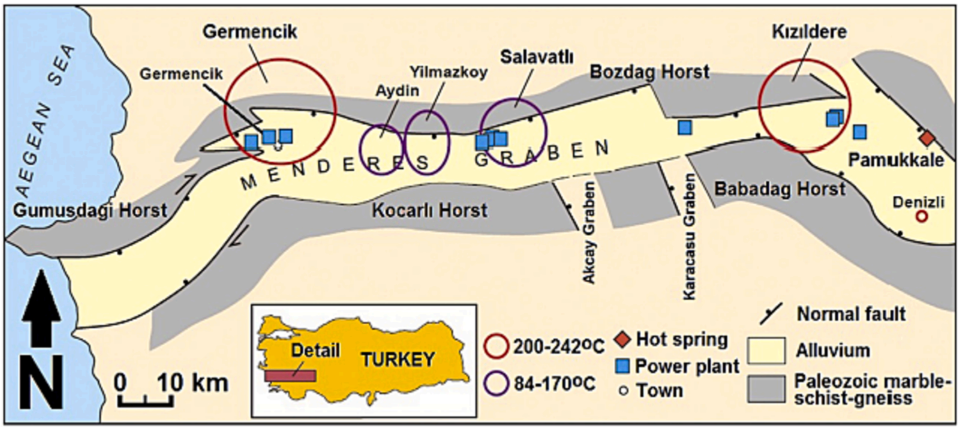


Fig. 3. Menderes Graben and the locations of Turkey's geothermal power plants [18].

Turkey was established in Denizli-Kızıldere with a capacity of 17.8 MW in 1984. Geothermal fields with high temperatures can be listed as follows. Aydın-Germencik (232 °C), Manisa- Salihli-Göbekli (182 °C), Çanakkale-Tuzla (174 °C), Aydın-Salavatlı (171 °C), Kütahya-Simav (162 °C), İzmir- Seferihisar (153 °C), Manisa-Salihli (150 °C), Aydın-Yılmazköy (142 °C), İzmir-Balçova (136 °C), İzmir-Dikili (130 °C) [22].

Conventional electricity is generated in geothermal fields with a reservoir temperature of more than 150 °C. With a system called a binary cycle, developed in recent years, electricity can be produced from a fluid with a temperature of up to $T > 80$ °C using gases with low evaporation points [23]. Various systems are available for converting vapor and liquid dominant systems into electrical energy. The fields that are easiest to use are the dry steam fields. The steam from the well is filtered and sent to a condensing turbine. In addition to the condenser, natural or mechanical cooling towers are used [24]. The most important residual heat source in geothermal fields is the separated liquid in the separator. Since conventional steam turbines use only steam, large amounts of remaining liquid are usually discharged into surface waters or injected underground. Binary technology has been developed to generate electricity from medium-temperature sources and recover residual heat by increasing thermal sources. Binary systems use a secondary working fluid with a low boiling temperature and high vapor pressure at low temperatures. This secondary fluid operates by a conventional Rankine cycle. With a suitable working fluid, binary systems can operate at inlet temperatures between 80 and 170 °C [25]. The majority of geothermal resources in Turkey fall into the low-medium enthalpy group. Therefore, using binary cycles to obtain electrical energy from these geothermal systems is essential. The choice of the system to be used (ORC or Kalina cycles) is determined primarily by the availability of the source and secondly by the economic studies to be carried out [26]. Turkey, which ranks seventh in the world with its geothermal wealth, will be able to meet up to 5 % of its total electrical energy need and up to 30 % of its heat energy need in heating with its geothermal potential. However, when their weight average is considered, Turkey has the potential to meet 14 % of its total energy (electricity + heat energy) needed with geothermal in Table 1 [27].

It is known that Turkey's especially Aegean region has rich geothermal resources. The widespread use of these resources in applications such as electricity generation, district heating, and greenhouse cultivation in the most efficient way and in the shortest time will

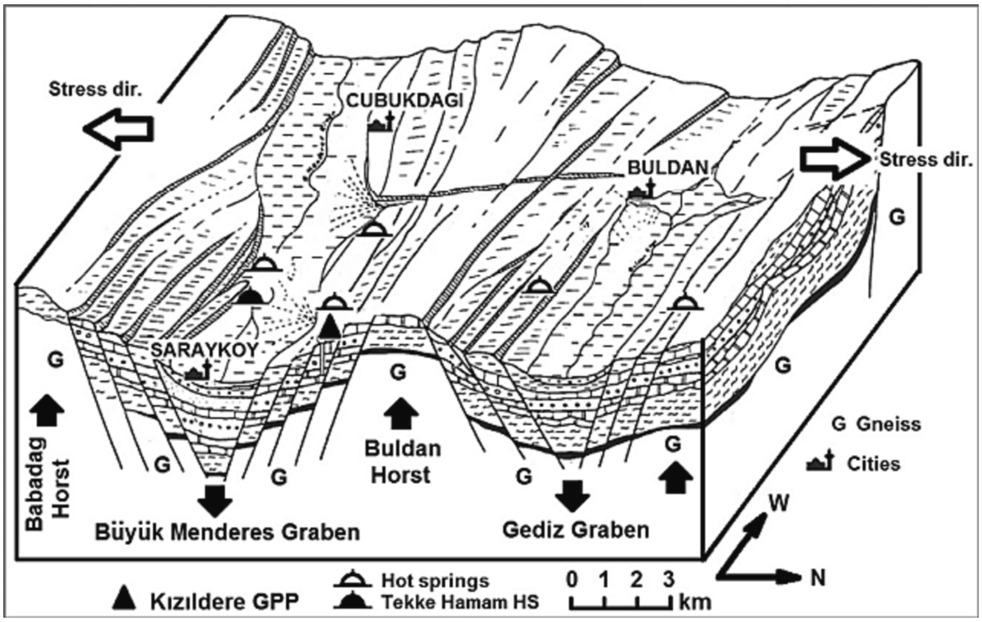


Fig. 4. Geological section showing the Büyük Menderes Graben and associated horsts [19].

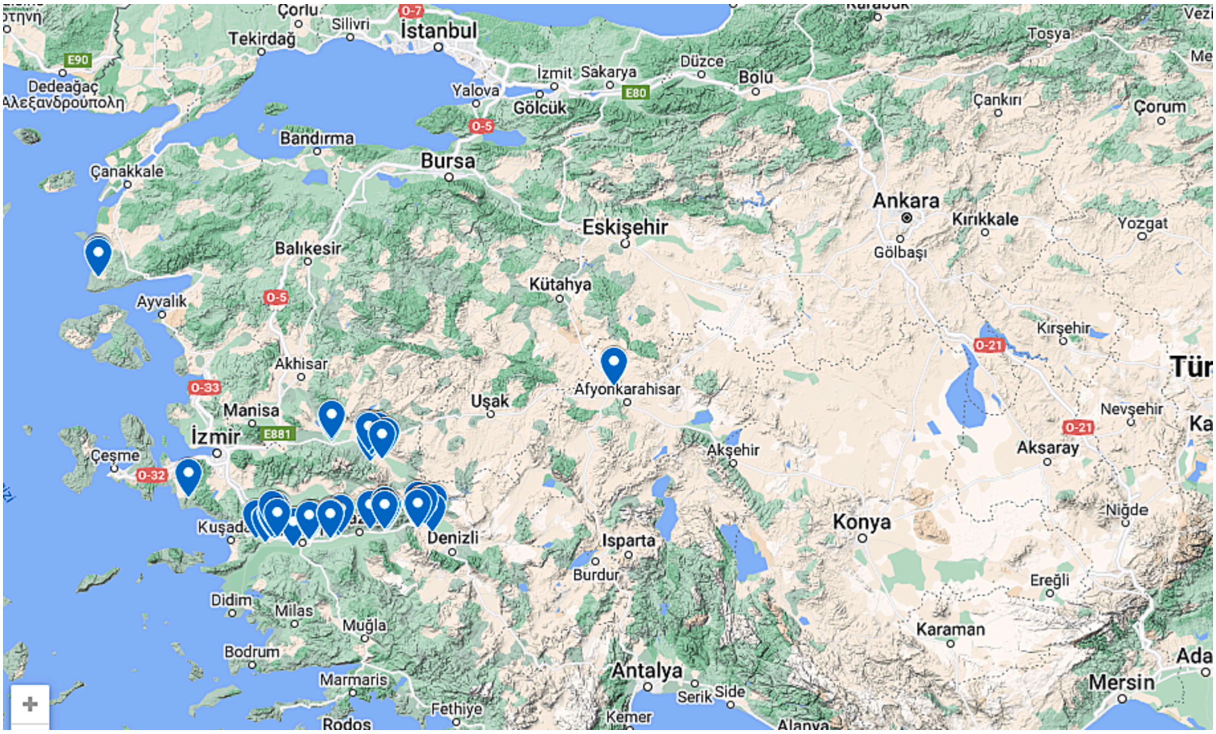


Fig. 5. Geothermal power plants map in Turkey [20].

significantly contribute to the solution of Turkey's energy problem. The most common usage area of geothermal energy is electricity production, and different thermodynamic cycles are used for this purpose [28]. These cycles can be classified as condenser and non-condenser dry steam cycles, single and double jet cycles, and secondary and combined spray/secondary cycles. In addition, the distribution of resources at the level of our country corresponds to the nature of our energy needs. There are sources suitable for high-temperature electricity generation in West and Northwest Anatolia, where the electricity deficit is high, and low-temperature sources are suitable for heating purposes in Central and Eastern Anatolia [29].

The proposed system for developing models for green hydrogen production from Turkey's geothermal resources comprises several key components. Firstly, it involves using geothermal wells to extract high-temperature geothermal fluids from underground reservoirs. These fluids, which contain valuable heat energy, are the primary input for hydrogen production. The geothermal fluids are transported to a hydrogen production plant via a dedicated pipeline system. At the hydrogen production plant, the geothermal fluids undergo a series of thermodynamic and chemical processes to produce hydrogen gas. Two potential methods for hydrogen production are considered: steam methane reforming (SMR) and electrolysis. In the SMR process, the

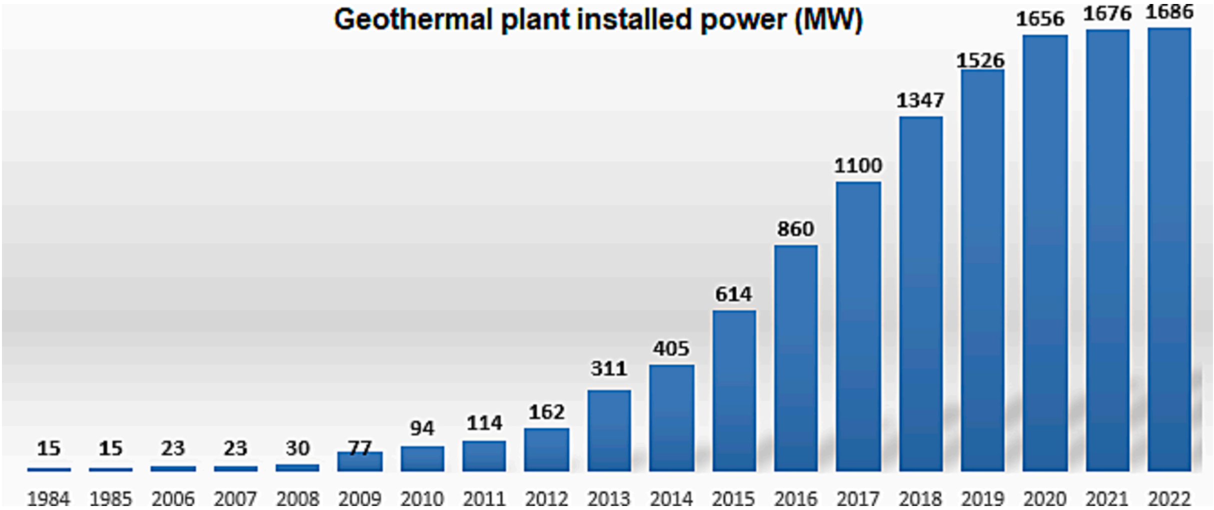


Fig. 6. Total installed power (MW) of geothermal power plants in Turkey [21].

Table 1
Potential mass flow rate and temperature of geothermal fields [27].

Geothermal resources	Mass flow rate (kg/s)	Temperature (°C)
Denizli-Kızıldere	250	200–242
Aydın-Germencik	765	200–232
Aydın-Salavatlı	454	171
Çanakkale-Tuzla	120	174
Kütahya-Simav	223	162
İzmir-Şerefhisar	264	153
Aydın-İmamköy	40	142
Manisa-Alaşehir-Kavaklıdere	6.5	215
Manisa-Caferbeyli	6.5	155
Aydın-Yılmazköy	27.96	142

geothermal fluids generate steam, mixed with methane, to produce hydrogen gas and carbon dioxide as a byproduct. The carbon dioxide can be captured and sequestered to minimize its environmental impact. Hydrogen gas can be purified and stored for various applications, such as fuel cell vehicles or industrial processes. Alternatively, electrolysis can be employed to produce hydrogen from geothermal fluids. This process involves using electricity from the geothermal power plant to split water molecules into hydrogen and oxygen gases through an electrolyzer. The hydrogen gas produced through electrolysis can also be purified, stored, and utilized for different purposes [30].

The working principle of the models developed for the green hydrogen production potential of Turkey's geothermal resources involves the integration of thermodynamics and thermoeconomics. The thermodynamic analysis focuses on quantifying the energy potential of geothermal resources and evaluating the efficiency of hydrogen production processes. It involves the application of fundamental thermodynamic principles, such as the first and second laws of thermodynamics, to assess heat transfer, energy conversion, and the overall system performance. Thermodynamic modeling helps determine the optimal operating parameters, including temperature, pressure, and heat transfer rates, to maximize the extraction and utilization of heat energy from geothermal fluids [31].

Additionally, the thermoeconomic analysis considers the economic aspects of the green hydrogen production process. It considers capital costs, operational expenses, and market prices of inputs and outputs to assess the economic viability and profitability of the proposed hydrogen production models. Thermoeconomic modeling helps identify the geothermal-based hydrogen production plant's most cost-effective configuration and operation strategies. Integrating thermodynamic and thermoeconomic analyses allows for a comprehensive evaluation of Turkey's geothermal resources' green hydrogen production potential. By optimizing the thermodynamic parameters while considering the economic constraints, the models provide insights into the feasibility, efficiency, and economic viability of utilizing geothermal resources for hydrogen production.

The outputs of these models can guide decision-making processes by providing critical information on the optimal design, operation, and economic performance of the geothermal-based hydrogen production plant. This information can support policymakers, investors, and energy stakeholders make informed choices regarding deploying sustainable and economically viable hydrogen production systems in Turkey's geothermal-rich regions [32].

This study focuses on developing models for assessing Turkey's geothermal resources' green hydrogen production potential. The analysis incorporates both thermodynamic and thermoeconomic considerations to provide a comprehensive understanding of the feasibility and viability of this renewable energy pathway. By examining the thermodynamic properties of geothermal resources and applying economic analysis, this research aims to determine the optimal conditions and configurations for efficient and economic hydrogen production from Turkey's geothermal fields. The potential and cost of green hydrogen produced from this region have been evaluated by giving the example of Afyon Geothermal Power Plant (AFJES), an actively operating geothermal power plant. Then, a general performance evaluation was made for other geothermal power plants, and the amount of hydrogen that could be produced and its costs were investigated. These results are given in the study's results section in the form of tables and graphics. Thermodynamic and economic analyses were made on real-time models in a computer environment with EES and Aspen Plus programs.

When the existing open literature is examined, there is no numerical analysis and simulation study on thermodynamic and thermoeconomic analysis and model development to investigate the green hydrogen production potential from geothermal energy under Turkey conditions. There are theoretically specific adaptation studies for some existing geothermal power plants, but there is no similar study where the appropriate potential for Turkey, in general, is revealed and considered. In addition, our study was carried out with detailed numerical analysis and simulations. The fact that no other directly similar study in this context shows that the paper is innovative.

2. System description and model working principle of plant

Fig. 7 shows the workflow of a geothermal power plant producing green hydrogen with geothermal energy. The plant is the combining of geo-fluid (between production well and re-injection well), ORC unit

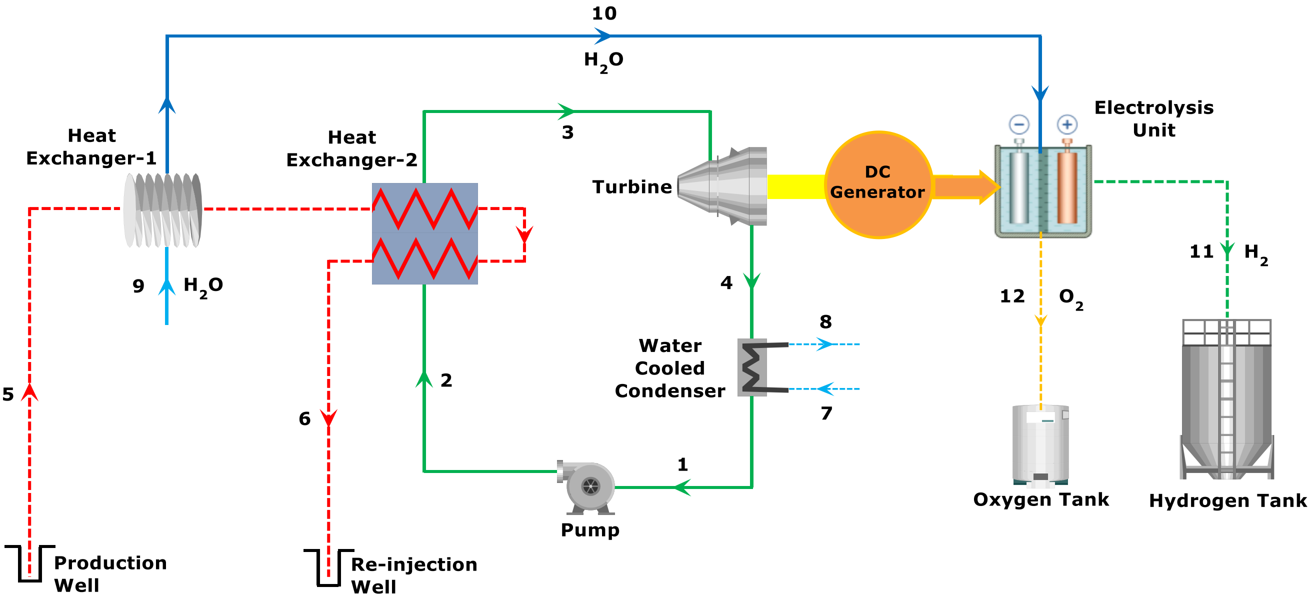


Fig. 7. The workflow of a geothermal plant producing green hydrogen with geothermal energy. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(pump, heat exchanger-2, turbine and condenser) and electrolysis unit (electrolysis tank, oxygen tank and hydrogen tank). Simply put, a geothermal power plant uses the energy of a geothermal fluid to supply various needs. The high-energy geo-fluid heats R134A which is the working fluid of the ORC unit in a heat exchanger (Heat Exchanger-2). The high pressure and heated ORC fluid drives the turbine and electricity is generated in the DC generator. The low pressure ORC fluid is cooled in condenser and pumped with high pressure to heat exchanger. The electricity produced is used in the electrolysis unit to produce green hydrogen. The geo-fluid is finally sent to re-injection well. In order to increase the electrolysis efficiency, the geothermal fluid heats the electrolysis water in a heat exchanger (Heat Exchanger-1) before driving ORC. The heating process is limited to 80 ℃ in order to keep the electrolysis water at 100 kPa pressure in the liquid phase. The hydrogen and oxygen produced in the electrolysis unit are sent to the tanks for storage.

3. Thermodynamic and thermoeconomic analysis of the plant

The thermodynamic analysis main equations required to predict the plant’s performance and the electrolysis units are given below. The thermodynamic analysis includes the first and second laws of thermodynamics. Thermoeconomic analysis combines the exergy data obtained from the thermodynamic analysis with the economic data. The main equations used in thermoeconomic analysis are also given below and are used to estimate unit product costs. The analysis’s ultimate goals are to estimate energy efficiency, exergy efficiency, net electric power, unit electricity cost, unit hydrogen cost, and hydrogen production. Analyzes and simulations are performed simultaneously in EES, and Aspen Plus supports their validity and applicability [33,34].

3.1. Thermodynamic analysis main equations

The energy efficiency of the geothermal power plant is the ratio of the net power produced to the total energy inlet power of the plant:

$$\eta_{th} = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \tag{1}$$

and the exergy efficiency is the ratio of the net power produced to the total exergy inlet of the plant.

$$\eta_{ex} = \frac{\dot{W}_{net}}{\dot{E}x_{in}} \tag{2}$$

The difference between the power produced by the ORC turbine and consumed by the pump and parasitic fan works power is the geothermal plant’s net power production (kJ/s).

$$\dot{W}_{net} = \dot{W}_{turbine} - \dot{W}_{pump} - \dot{W}_{parasitic} \tag{3}$$

Electrolysis is breaking down water into hydrogen and oxygen with electrical energy. Electrolysis is an endothermic thermochemical process. While doing the thermodynamic analysis of this process, enthalpy and entropy properties in the molecular state are used. The decomposition of water into hydrogen and oxygen by electrolysis is provided by the current flow between the electrodes and electrolyte solution liquid with high ionic conductivity [35].

H_2O (liquid) + Electrical energy → $H_2 + ½\, O_2$ (4).

For this reaction to occur, the minimum required electrical work must be applied to the electrodes. The find minimum electrical work, the Gibbs free energy equation is used. In laboratory conditions, one mole of hydrogen gas and half a mole of oxygen gas are formed due to the electrolysis of one mole of water. The Gibbs formation function is the minimum work required for the electrolysis process. In other words, the amount of reversible work must be given to the electrolysis unit to produce one kilogram of hydrogen. The general statement is as follows [35].

$$W_{\min} = \Delta G = \Delta H - T\Delta S \tag{5}$$

Here, ΔG is the change in Gibbs energy (reversible work or minimum work), T is the temperature, and ΔS is the entropy difference. ΔG represents the energy that needs to be supplied as electricity, and $T\Delta S$ represents the thermal energy. ΔH represents the total heat energy released in the reaction. The total required energy is ΔH. The minimum electrolysis work required for hydrogen can be found using the equation below. The molar mass M of hydrogen is 2.016 kg/kmol [36].

$$w_{\min,H_2} = \frac{\Delta G}{M_{H_2}} \tag{6}$$

Here, $w_{\min,H2}$ represents the minimum work required to produce 1 kg of hydrogen. This value increases when the electrolysis cell efficiency is taken into account. Thus, we can calculate the actual work required to produce 1e kilogram of hydrogen as $w_{\text{min,H2}}/\eta_{\text{electrolysis}}$. We can find the mass flow rate (kg H_2/s) of the hydrogen produced from the system by the ratio of the electrical power (kJ/s) produced in geothermal power cycles and used for electrolysis to this actual work (kJ/kg H_2) [36]

$$\dot{m}_{H_2} = \frac{\dot{W}_{net}}{w_{electrolysis}} \tag{7}$$

where $w_{electrolysis}$ is the actual work consumption of water electrolysis in kJ/kg H_2. Also, when the energy efficiency of electrolysis is the ratio of hydrogen energy produced to the net power, the exergy efficiency of electrolysis is the ratio of hydrogen exergy produced to the net power [36]:

$$\eta_{th,electrolysis} = \frac{\dot{m}_{H_2} LHV}{\dot{W}_{net}} \tag{8}$$

$$\eta_{exelectrolysis} = \frac{\dot{m}_{H_2} ex_{H_2}}{\dot{W}_{net}} \tag{9}$$

where LHV and ex_{H_2} are lower heating value of hydrogen and the specific exergy of hydrogen produced, respectively.

3.2. Thermoeconomic analysis main equations

The economic analysis aims to evaluate the energy cost of green hydrogen produced by the plant and compare it with the market price. Capital Recovery Factor (CRF) must first calculate total cost rates in thermoeconomic analysis. CRF is defined as [37]

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{10}$$

where i and n are interest rate and plant operating life, respectively. Total cost rate is [37]

$$\dot{Z}_k = \frac{C_k(CRF)\phi}{(n \times 3600)} \tag{11}$$

where C_k and ϕ are equipment purchasing cost and operation and maintenance factor, respectively.

Exergy costing usually includes cost balances formulated for each component separately. In a cost balance applied to system component k, the sum of the cost ratios associated with all exergy flows out of the component equals the sum associated with all exergy flows entering the component and the total cost ratio. Accordingly, the following equation can be written for a component that receives heat transfer and produces power [37]

$$\dot{C}_k = c_k.\dot{E}x_k \tag{12}$$

$$\dot{C}_k = c_k.\dot{W}_k \tag{13}$$

$$\dot{C}_k = c_k.\dot{Q}_k \tag{14}$$

$$\sum_i \dot{C}_{i,k} + \dot{C}_{q,k} + \dot{Z}_k = \sum_e \dot{C}_{e,k} + \dot{C}_{w,k} \tag{15}$$

when $\dot{C}$ is the exergy cost ratio, the subscripts of i and e represent the input and exit, respectively. The assumptions made and plant properties for the analysis are given in Table 2.

Table 2
The assumptions made and plant properties for the analysis [38,39].

Parameter	Value
The geo-fluid temperature (°C)	110
The geo-fluid mass flow rate (kg/s)	150
Isentropic efficiencies of turbine and pump	85 %
The ambient pressure / temperature (kPa / °C)	100 / 25
Rise of pressure in ORC	6
LHV (kJ/kg)	120 210
The plant operating life (year)	20
Interest rate	10 %
Operation and maintenance correction factor	1.06
Unit geo-fluid cost ($/kJ)	1.372×10^{-6}
Unit R134A cost ($/kJ)	3.099×10^{-6}

4. Results and discussion

4.1. Thermodynamic and thermoeconomics analysis results

This section presents thermodynamic and thermoeconomic analysis results of the AFJES geothermal plant and hydrogen production potentials of other geothermal plants in Turkey. Table 3 and Table 4 show the plant's steady flow thermodynamic data and thermodynamic analysis results, respectively. As a result of the analysis performed by EES, the plant produces 4132 kW net power with 150 kg/s geo-fluid at 110°C. R134a, a popular and efficient fluid at the temperature levels mentioned as ORC working fluid, has been assumed. The energy and exergy efficiency of the plant were calculated as 14.89 % and 63.9 %, respectively. As the electrolysis unit's thermodynamic analysis is examined, to improve energy efficiency, electrolysis water is heated up to 80°C to be included in the electrolysis process in liquid form and hot. So, the energy and exergy efficiencies of the electrolysis are calculated as 85.27 % and 77.63 %.

This study considers the PEM electrolyzer widely used in low-temperature water electrolysis. PEM electrolyzers are the most common water electrolysis application known for being commercialized, efficient, and efficient in different operating conditions. Thermodynamic modeling of a PEM electrolysis unit with an energy conversion efficiency of 75 % is considered. At 25 °C and 1 atm conditions, the work required to produce 1 kg of hydrogen from the ideal water electrolysis is calculated as 117,650 k/kg. Accordingly, the actual work required to produce 1 kg of hydrogen with a 75 % PEM water electrolysis was calculated as 156,867 kJ/kg (117650/0.75). In this study, since the electrolysis water is easily preheated up to 80 °C with geothermal water, the required actual electrolysis work has been reduced to 150,882 kJ/kg. This corresponds to approximately 42.0 kWh of electrical energy to produce 1 kg of hydrogen from water electrolysis [40].

The thermoeconomic results of the power plant are given in Table 5. According to the results of the thermoeconomic analysis, the unit cost of the electricity and hydrogen produced in the power plant was determined as 0.01671 $/kWh and 1.684 $/kg, respectively.

The study includes the case study and the investigation of hydrogen production and cost depending on different geo-fluid temperatures. In Figs. 2 and 3, the changes in the unit electricity cost and net power depending on geo-fluid temperature and the changes in the unit hydrogen cost and the hydrogen production depending on geo-fluid temperature are given parametrically, respectively. As seen in Fig. 8, as the geo-fluid temperature increases, the inlet energy of the ORC unit increases, producing more net power. With higher-capacity electricity production under current conditions, electricity becomes cheaper, and unit electricity cost decreases. So, as seen in Fig. 9, more and cheaper green hydrogen can be produced with higher capacity and cheaper electricity.

4.2. Aspen plus modeling and analysis results of the plant

Fig. 10 shows the model of the AFJES geothermal power plant designed and hydrogen production in the Aspen Plus program. When the steady-state thermodynamic data of the model are examined, it is seen that they are almost the same as the data obtained in the EES. First, 110°C geo-fluid heats the electrolysis water to 80°C in a heat exchanger. Thus, the efficiency of electrolysis increases. It then heats the ORC fluid R134A in another heat exchanger. The fluid at 100°C and 3000 kPa drives the turbine and expands by generating electricity. The fluid at

Table 3
The steady flow thermodynamic data of the geothermal-assisted hydrogen production plant.

State	Fluid	T (℃)	P (kPa)	$\dot{m}$(kg/s)	h (kJ/kg)	s (kJ/kgK)	$\dot{E}$x(kW)
1	R134A	15.71	500	137.5	73.33	0.2802	5 919
2	R134A	17.18	3 000	137.5	75.7	0.2815	6 194
3	R134A	100	3 000	137.5	305	0.9497	10 338
4	R134A	29.5	500	137.5	272.5	0.9688	5 098
5	Geo-fluid	110	143.2	150	461.3	1.419	6 466
6	Geo-fluid	60	143.2	150	251.2	0.8312	1 194
7	Water	10	100	654.7	41.99	0.151	983.7
8	Water	20	100	654.7	83.84	0.2962	45.05
9	Electrolysis water	27	100	0.2447	113.2	0.3949	0.007863
10	Electrolysis water	80	100	0.2447	−13 319	10.8	12.34
11	Hydrogen	69	100	0.0274	791.4	67.25	3 208
12	Oxygen	69	100	0.2173	50.68	6.567	26.99

Table 4
Thermodynamic analysis results of the system.

Parameter	Value
$\eta_{th}(\%)$	14.89
$\eta_{ex}(\%)$	63.9
$\dot{W}_{net}(kW)$	4 132
$\dot{m}_{H_2}(kg/s)$	0.0274
$\eta_{thelectrolysis}$	85.27
$\eta_{exelectrolysis}$	77.63

Table 5
Thermoeconomic analysis results of the geothermal-assisted hydrogen production.

State	c ($/GJ)	C ($/h)
1	3.099	66.03
2	3.273	72.98
3	3.354	124.8
4	3.354	61.54
5	1.372	31.94
6	−3.584	−15.41
7	0	0
8	0	0
9	0	0
10	0	0
11	14.01	161.8
12	0	0
Unit electricity cost ($/kWh)		0.01671
Unit hydrogen cost ($/kg)		1.684
Hydrogen cost rate ($/h)		166.11

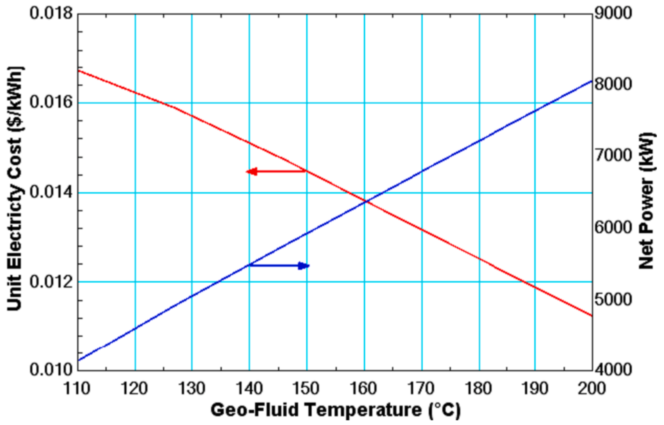


Fig. 8. The changes in the unit electricity cost and net power depend on geo-fluid temperature.

30℃ and 500 kPa is cooled in the condenser and becomes liquid. Then, the fluid is pumped to 3000 kPa and sent back to the heat exchanger to be heated. The ORC turbine generates 4461 kW in this cycle, while the ORC pump consumes 326 kW. Therefore, the net output power is determined as 4135 kW. This data is almost the same as obtained in EES (4132 kW). The geo-fluid is then sent back to the re-injection well. The produced 4135 kW net power and water at 80℃ are used in the electrolysis unit, and hydrogen and oxygen are obtained. Since the reaction is endothermic, the temperature becomes 69℃. As a result of electrolysis, approximately 99 kg/h of hydrogen and 782 kg/h of oxygen are produced from 881 kg/h of water. This value is almost the same as the data in Table 3. The green hydrogen and oxygen produced are sent to the tanks for use.

4.3. Parametric study of hydrogen production by geothermal resources in Turkey

In this section, 10 geothermal resources suitable for electricity generation in Turkey were identified, and their thermodynamic and economic analyses were performed. The electricity produced is used as the necessary work for hydrogen production by water electrolysis. No such study has been found before regarding geothermal resources in Turkey. The research is only about electricity production and the heating systems connected, as given above, as combined systems. Here, energy and economic performance parameters have been calculated considering the sources' maximum temperatures and flow rates. At the same time, graphs showing the varying hydrogen production amount and unit mass of hydrogen production cost for specific temperature ranges for each source were obtained. Geothermal well locations, flow rates, and temperatures to be used in the calculations are seen in Table 6. These plants' green hydrogen production potentials have been calculated using the data in this list and the EES coding in the current study. The results have been presented in Table 6, and it has been seen that they keep pace with the comments made for Figs. 11 and 12 [41].

The validation of the AFJES thermodynamic model producing hydrogen is given in Table 7. As seen in the table, the proposed study's model produces hydrogen cheaply and efficiently.

5. Conclusion

The development of models for assessing the green hydrogen production potential of Turkey's geothermal resources through thermodynamics and thermoeconomics analyses has provided valuable insights into the feasibility, efficiency, and economic viability of this renewable energy pathway. The findings of this case study hold significant implications for Turkey's energy sector and contribute to its sustainable development goals. Through the thermodynamic analysis, the research explored the thermophysical properties of geothermal fluids and evaluated the potential for harnessing the available heat for hydrogen production. This analysis provides critical information for maximizing the

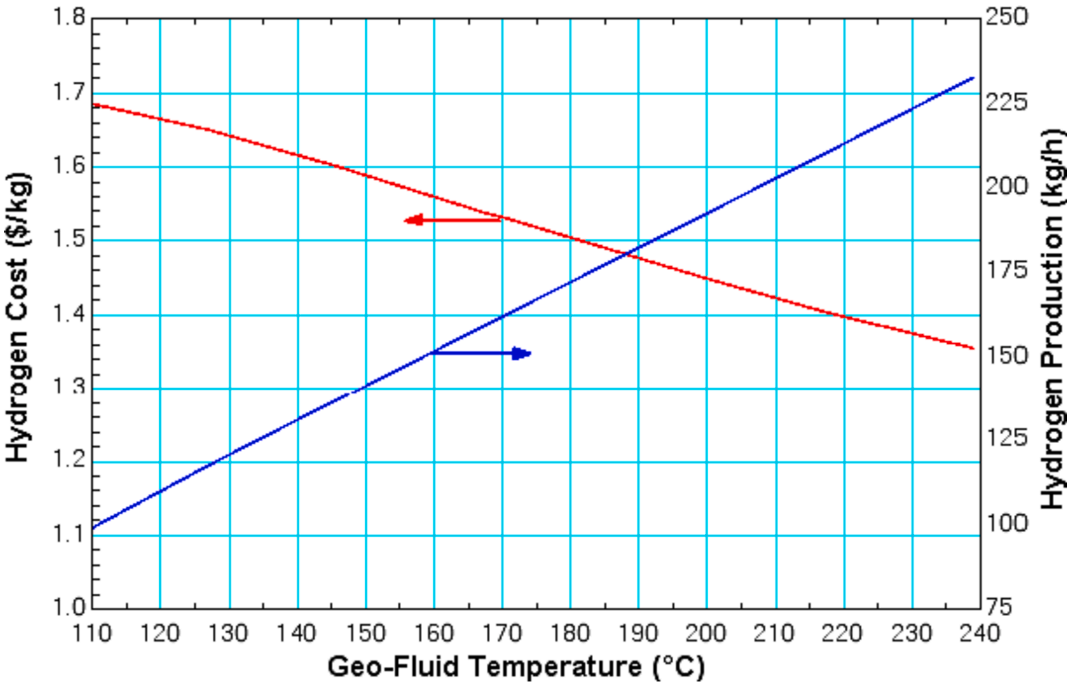


Fig. 9. The changes in the unit hydrogen cost and the hydrogen production depend on geo-fluid temperature.

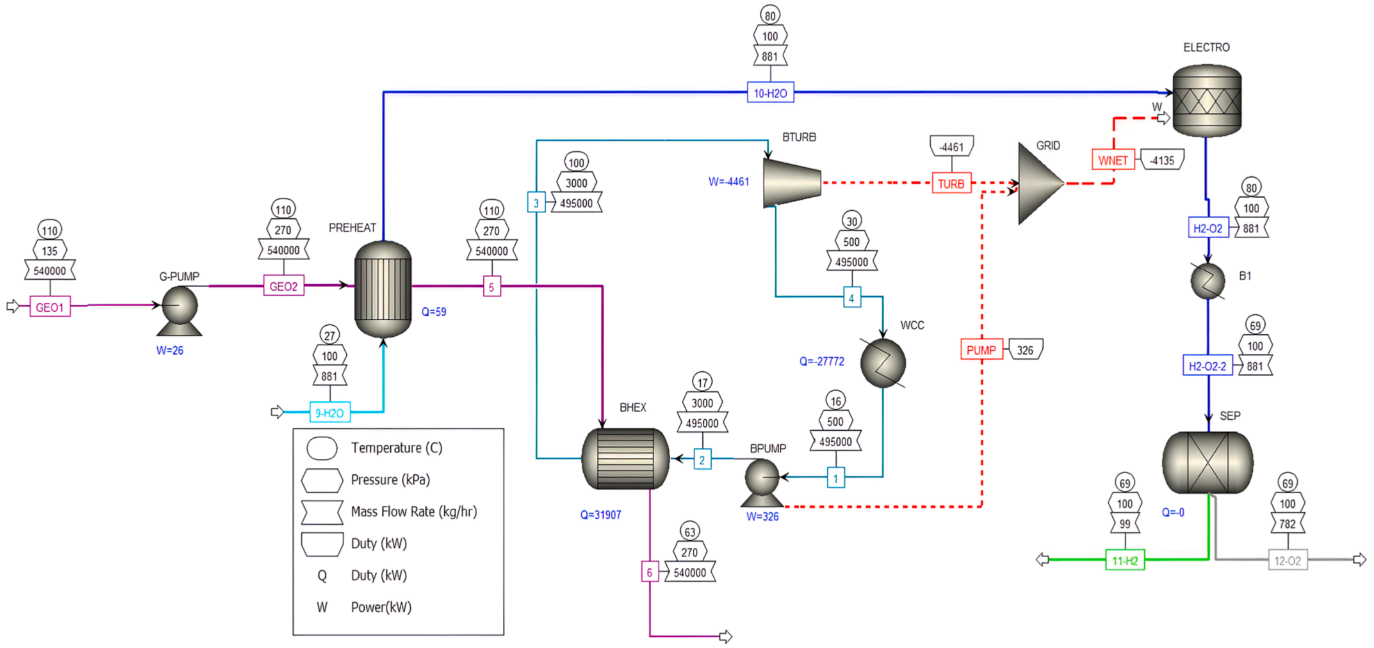


Fig. 10. Model of the AFJES geothermal power plant designed and hydrogen production in the Aspen Plus program.

extraction and utilization of heat energy from geothermal fluids, optimizing the hydrogen production process. Furthermore, the thermoeconomic analysis delved into the economic aspects of green hydrogen production from geothermal resources. By considering capital costs, operational expenses, and market prices of inputs and outputs, this study evaluated the financial feasibility and competitiveness of the proposed hydrogen production models. Integrating economic considerations alongside the thermodynamic analysis provided a holistic understanding of the economic viability and potential profitability of utilizing Turkey's geothermal resources for green hydrogen production.

The outcomes of this research offer valuable guidance for decision-making processes concerning deploying sustainable and economically viable hydrogen production systems in Turkey's geothermal-rich regions. Policymakers, investors, and energy stakeholders can use the findings to make informed choices regarding the geothermal-based hydrogen production plants' design, operation, and economic performance. This, in turn, can drive the adoption of innovative and environmentally friendly energy solutions, contributing to Turkey's energy transition goals and reducing greenhouse gas emissions. Moreover, the knowledge gained from this case study can have broader implications beyond Turkey, serving as a reference for other countries with similar geothermal resources. By understanding geothermal sources' green

Table 6
The hydrogen production potentials of various geothermal plants in Turkey [41].

Location	Geo-fluid Temperature (℃)	$\dot{W}_{net}$ (MW)	Electricity cost ($/kWh)	Hydrogen cost ($/kg)	Hydrogen production potential (kg/h)
Aydın-Germencik	239	163	0.008043	1.327	4163
Germencik Unit 2	218	47	0.009579	1.377	1201
Manisa-Alaşehir	200	40	0.01062	1.422	1022
Manisa	200	15	0.01087	1.433	383
Manisa-Sarıkız	200	10	0.01108	1.442	255.3
Manisa-Alaşehir: Turkerler	200	24	0.01072	1.426	612.8
Manisa-Alaşehir	200	30	0.01067	1.424	766
Manisa-Merkez	200	24	0.01072	1.426	612.8
Salavatlı-Sultanhisar	171	34	0.01241	1.499	868.6
Salavatlı: Dora 4	171	17	0.001258	1.506	434.3
Salavatlı: Dora 5	171	17	0.001258	1.506	434.3
Salihli-Caferbeyli-1	168	15	0.01281	1.516	382.9
Salihli-Manisa: Caferbeyli-2	168	15	0.01281	1.516	382.9
Aydın-Hıdırbeyli	146	24	0.01398	1.566	612.8
Aydın-Hıdırbeyli	146	24	0.01398	1.566	612.8
Aydın-Nazilli	127	20	0.01498	1.61	511

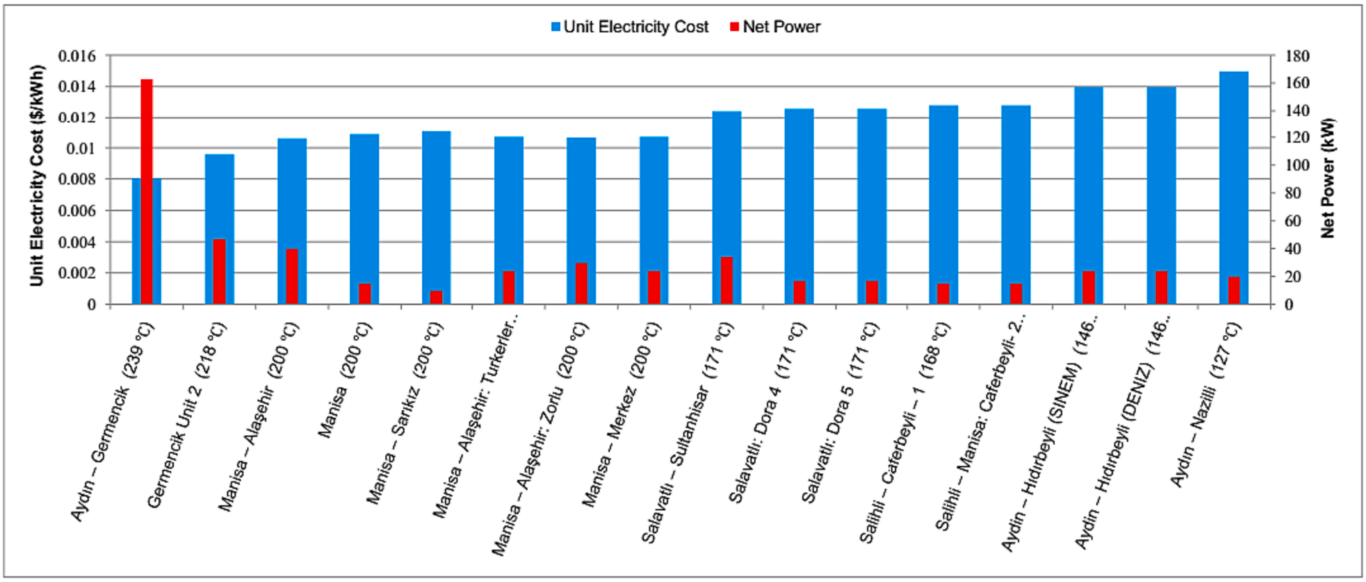


Fig. 11. Variation of net power and unit cost of electricity according to different geothermal power plants in Turkey.

hydrogen production potential, these countries can accelerate their energy transition efforts, tapping into the vast renewable energy potential and reducing reliance on fossil fuels.

In conclusion, developing models for assessing Turkey's geothermal resources' green hydrogen production potential through thermodynamics and thermoeconomics analyses represents a significant step towards achieving a sustainable, low-carbon energy future. By optimizing the utilization of geothermal resources for hydrogen production, Turkey can unlock a clean energy pathway while capitalizing on its abundant geothermal resources. This research contributes to the broader global goal of mitigating climate change, fostering energy security, and driving sustainable development.

In this study, thermodynamic and thermoeconomic analysis of AFJES, which produces electricity with 150 kg/s hot water at 110℃, were performed. Analyzes were made in EES and Aspen Plus programs. The data obtained from the programs are almost the same.

Thermodynamic analysis results are as follows:

- The plant's energy efficiency, exergy efficiency, and net power are 14.89 %, 63.9 %, and 4132 kW, respectively.
- With a net electrical power of 4132 kW, approximately 99 kg/h of hydrogen and 782 kg/h of oxygen can be produced in the electrolysis unit. As hydrogen can be used when energy is needed, oxygen can be used for patients with respiratory problems.

Thermoeconomic analysis results are as follows:

- The unit electricity cost of the plant is 0.01671 $/kWh.
- The cost of hydrogen produced with 4132 kW of net electrical power is calculated as 1.684 $/kg.
- In addition, a parametric optimization was carried out on hydrogen production and unit cost.

Parametric optimization results are as follows:

- As the geo-fluid temperature increases, the net power increases under current conditions.
- As the net power increases, the electricity cost decreases.
- This allows more hydrogen to be produced more cheaply.

Based on these results, the hydrogen production potentials of geothermal power plants with higher geo-fluid temperatures in Turkey were also investigated. Considering the geo-fluid temperatures and net power of the plants, the following results were obtained:

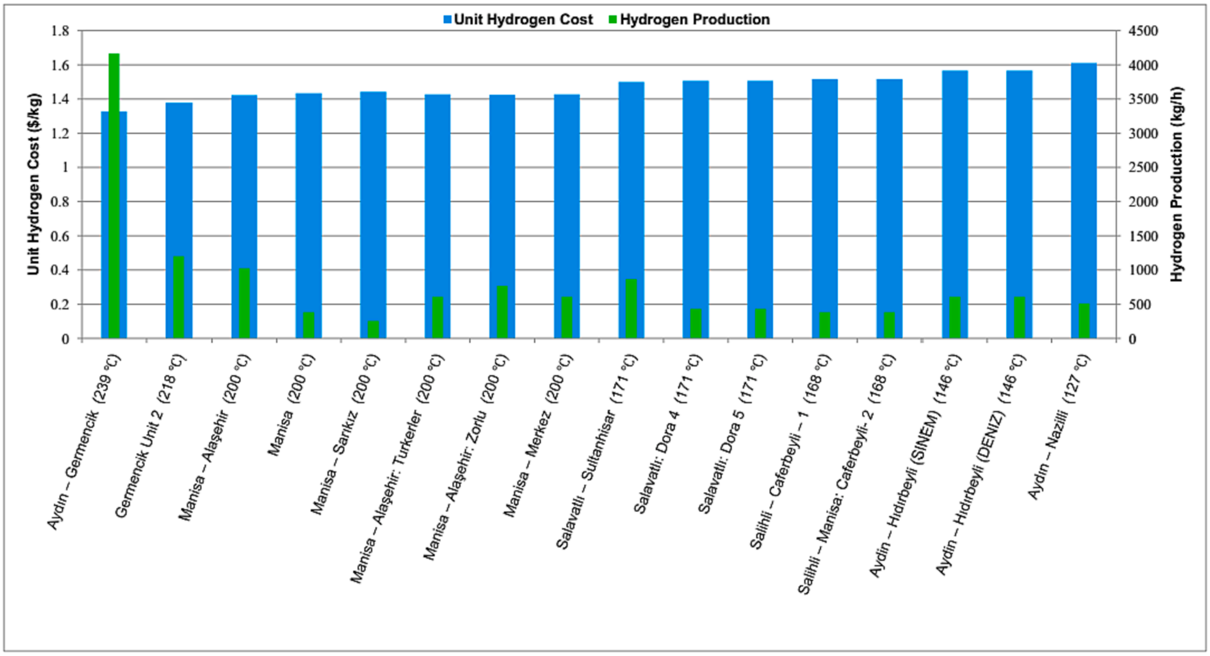


Fig. 12. Variation of hydrogen production potential and unit cost of hydrogen according to different geothermal power plants in Turkey.

Table 7
System validation of the proposed study.

Study	Hydrogen production (kg/h)	Hydrogen cost rate ($/h)	Exergy efficiency (%)	Net power (MW)
Sangesaraki et al. [42]	59.92	181.71	25.27	4.03
Yilmaz and Kanoglu [43]	189.684	206	38.37	7.978
Yuksel and Ozturk [44]	270	297	32.15	8.5
Proposed study	99	166.11	63.9	4.132

- When the plants with the same net power are compared, it is seen that the increase in geo-fluid temperature reduces unit electricity and hydrogen costs. However, hydrogen production remains constant.
- When the plants with the same geo-fluid temperature are compared, it is seen that the increase in the net power of the plant increases the hydrogen production and reduces the unit electricity and hydrogen costs.

CRediT authorship contribution statement

Muhammed Arslan: . **Ceyhun Yilmaz:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

References

[1] Hepbasli A, Canakci C. Geothermal district heating applications in Turkey: a case study of Izmir-Balcova. Energ Conver Manage 2003;44(8):1285–301.
[2] Guler OF, Sen O, Yilmaz C, Kanoglu M. Performance evaluation of a geothermal and solar-based multigeneration system and comparison with alternative case studies: Energy, exergy, and exergoeconomic aspects. Renew Energy 2022;200:1517–32.
[3] Song H, Liu Y, Bian H, Shen M, Lin X. Energy, environment, and economic analyses on a novel hydrogen production method by electrified steam methane reforming with renewable energy accommodation. Energ Conver Manage 2022;258:115513.
[4] Sen O, Guler OF, Yilmaz C, Kanoglu M. Thermodynamic modeling and analysis of a solar and geothermal assisted multi-generation energy system. Energ Conver Manage 2021;239:114186.
[5] Cao Y, Haghghi MA, Shamsaiee M, Athari H, Ghaemi M, Rosen MA. Evaluation and optimization of a novel geothermal-driven hydrogen production system using an electrolyser fed by a two-stage organic Rankine cycle with different working fluids. J Storage Mater 2020;32:101766.
[6] Cao Y, Dhahad HA, Togun H, Hussen HM, Anqi AE, Farouk N, et al. Exergy, exergoeconomic and multi-objective optimization of a clean hydrogen and electricity production using geothermal-driven energy systems. Int J Hydrogen Energy 2022;47(62):25964–83.
[7] Li H, Tao Y, Zhang Y, Fu H. Two-objective optimization of a hybrid solar-geothermal system with thermal energy storage for power, hydrogen and freshwater production based on transcritical CO_2 cycle. Renew Energy 2022;183:51–66.
[8] Li K, Ding YZ, Ai C, Sun H, Xu YP, Nedaei N. Multi-objective optimization and multi-aspect analysis of an innovative geothermal-based multi-generation energy system for power, cooling, hydrogen, and freshwater production. Energy 2022;245:123198.
[9] Sohani A, Delfani F, Hosseini M, Sayyaadi H, Karimi N, Li LK, et al. Dynamic multi-objective optimization applied to a solar-geothermal multi-generation system for hydrogen production, desalination, and energy storage. Int J Hydrogen Energy 2022;47(74):31730–41.
[10] Manesh MK, Rabeti SM, Nourpour M, Said ZJSET. Energy, exergy, exergoeconomic, and exergoenvironmental analysis of an innovative solar-geothermal-gas driven polygeneration system for combined power, hydrogen, hot water, and freshwater production. Sustainable Energy Technol Assess 2022;51:101861.
[11] Xing L, Li J. Proposal of biomass/geothermal hybrid driven poly-generation plant centering cooling, heating, power, and hydrogen production with CO_2 capturing: Design and 3E evaluation. Fuel 2022;330:125593.
[12] Alirahmi SM, Assareh E, Pourghassab NN, Delpisheh M, Barelli L, Baldinelli A. Green hydrogen & electricity production via geothermal-driven multi-generation system: Thermodynamic modeling and optimization. Fuel 2022;308:122049.
[13] Karayel GK, Javani N, Dincer I. Effective use of geothermal energy for hydrogen production: A comprehensive application. Energy 2022;249:123597.
[14] Yilmaz F. Development and modeling of the geothermal energy based multigeneration plant for beneficial outputs: Thermo-economic and environmental analysis approach. Renew Energy 2022;189:1074–85.

[15] Atiz A, Karakilcik H, Erden M, Karakilcik M. Assessment of power and hydrogen production performance of an integrated system based on middle-grade geothermal source and solar energy. Int J Hydrogen Energy 2021;46(1):272–88.
[16] Uğur A, Ulugergerli EU, Kutlu S. The assessment of geothermal potential of Turkey by means of heat flow estimation. Bulletin of the Mineral Research and Exploration 2014;149(149):201–10.
[17] Turkey General Directorate of Mineral Research and Exploration. (2023). https://www.mta.gov.tr/v3.0/arastirmalar/jeotermal-enerji-arastirmalari.
[18] Fridriksson, T., Merino, A. M., Orucu, A. Y., & Audinet, P. (2017). Greenhouse gas emissions from geothermal power production. In Proceedings, 42nd Workshop on Geothermal Reservoir Engineering. California: Stanford University, Stanford.
[19] Faulds JE, Bouchot V, Moeck I, Oguz KJGRCT. Structural controls on geothermal systems in western Turkey: A preliminary report. Geothermal Resources Council Transactions 2009;33:375–82.
[20] https://www.mta.gov.tr/, Acces in 2023.
[21] https://jesder.org/, Acces in 2023.
[22] Dursun B, Gokcol C. The role of geothermal energy in sustainable development of Turkey. Energy Explor Exploit 2012;30(2):207–22.
[23] Ahmed A, Esmaeil KK, Irfan MA, Al-Mufadi FA. Design methodology of organic Rankine cycle for waste heat recovery in cement plants. Appl Therm Eng 2018;129:421–30.
[24] DiPippo R. Geothermal energy Electricity generation and environmental impact. Energy Policy 1991;19(8):798–807.
[25] Kanoglu M, Bolatturk A. Performance and parametric investigation of a binary geothermal power plant by exergy. Renew Energy 2008;33(11):2366–74.
[26] Kostowski W, Pajączek K, Pociecha A, Kalina J, Niedzielski P, Przybył A. Methods of waste heat recovery–A compressor station case study. Energ Conver Manage 2019;197:111837.
[27] Benli H. Potential of renewable energy in electrical energy production and sustainable energy development of Turkey: Performance and policies. Renew Energy 2013;50:33–46.
[28] Moya D, Aldás C, Kaparaju P. Geothermal energy: Power plant technology and direct heat applications. Renew Sustain Energy Rev 2018;94:889–901.
[29] Serpen U, Aksoy N, Öngür T, Korkmaz ED. Geothermal energy in Turkey: 2008 update. Geothermics 2009;38(2):227–37.
[30] Maestre VM, Ortiz A, Ortiz I. Transition to a low-carbon building stock. Techno-economic and spatial optimization of renewables-hydrogen strategies in Spain. J Storage Mater 2022;56:105889.
[31] Pathak SK, Tyagi VV, Chopra K, Kalidasan B, Pandey AK, Goel V, et al. Energy, exergy, economic and environmental analyses of solar air heating systems with and without thermal energy storage for sustainable development: A systematic review. J Storage Mater 2023;59:106521.
[32] Koohi Fayegh S, Rosen MA. A review of energy storage types, applications and recent developments. J Storage Mater 2020;27:101047.
[33] F-Chart Software, EES (Engineering Equation Solver) (2022). In: F-Chart Software, Inter-net Website, www.fchart.com/ees/ees.shtml.
[34] Aspen Plus. (2015). Engineering Economic Analysis Library.
[35] Yilmaz C, Kanoglu M. Thermodynamic evaluation of geothermal energy powered hydrogen production by PEM water electrolysis. Energy 2014;69:592–602.
[36] Yilmaz C. Life cycle cost assessment of a geothermal power assisted hydrogen energy system. Geothermics 2020;83:101737.
[37] Bejan A, Tsatsaronis G, Moran MJ. Thermal design and optimization. John Wiley & Sons; 1995.
[38] Yilmaz C, Koyuncu I. Thermoeconomic modeling and artificial neural network optimization of Afyon geothermal power plant. Renew Energy 2021;163:1166–81.
[39] Sahin, C. (2016). Electricity Generation with Organic Rankine Cycle (Orc) In Low Temperature Geothermal Field and Modelling of Afyon Geothermal Electric Production Co., Electrical and Electronics Engineering (Doctoral dissertation, MS Thesis).
[40] Correa G, Volpe F, Marocco P, Muñoz P, Falagüerra T, Santarelli M. Evaluation of levelized cost of hydrogen produced by wind electrolysis: Argentine and Italian production scenarios. J Storage Mater 2022;52:105014.
[41] Arslan M, Yılmaz C. Investigation of green hydrogen production and development of waste heat recovery system in biogas power plant for sustainable energy applications. Int J Hydrogen Energy 2023;48(69):26652–64.
[42] Sangesaraki AG, Gharehghani A, Mehrenjani JR. 4E analysis and machine learning optimization of a geothermal-based system integrated with ejector refrigeration cycle for efficient hydrogen production and liquefaction. Int J Hydrogen Energy 2023;48(82):31875–904.
[43] Yilmaz C, Koyuncu I, Alcin M, Tuna M. Artificial Neural Networks based thermodynamic and economic analysis of a hydrogen production system assisted by geothermal energy on Field Programmable Gate Array. Int J Hydrogen Energy 2019;44(33):17443–59.
[44] Yuksel YE, Ozturk M. Thermodynamic and thermoeconomic analyses of a geothermal energy based integrated system for hydrogen production. Int J Hydrogen Energy 2017;42(4):2530–46.