Impact of Different Solar Trackers on Hydrogen Production: A Case Study in Iran

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Received 2 June 2021; Accepted 21 September 2022; Published 18 October 2022

Academic Editor: Ahmad Umar

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Currently, solar energy is considered one of the most suitable options for overcoming the problems of fossil fuel depletion, and global warming. Also, the high costs associated to photovoltaic systems, renders the maximum utilization of solar cells, a fundamental and undeniable necessity. Technical-economic-environmental analysis, using HOMER software, was performed under four different scenarios: without the tracker, with the horizontal axis tracker, with the vertical axis tracker, and with the dual-axis tracker. Consequently, the best configuration was chosen for each scenario. The optimal system for all four scenarios, in the circumstance of disconnection from the grid, only involves the solar cells, while in the circumstance of connection to the grid, both the solar cells and the wind turbine are included. The results demonstrate that in the off-grid situation, the scenario involving the use of a vertical axis tracker would be the most cost-effective, with the price of 0.812 $/kWh for energy produced, while the lowest price for producing one kg of hydrogen is $77.97 is attributable to the scenario without the use of a solar tracker. In the circumstance of being connected to the power grid, the scenario involving the use of a vertical axis tracker would be most cost-effective, with the price of each kWh of energy produced equal to $ 0.223. At the price of $29.33 per kilogram, the scenario involving the use of a vertical axis tracker would also be most suitable for the production of hydrogen.

Another important fact revealed through the results, is the crucial role of dump load, in the provision of the heat required in an off-grid situation. However, dump load is not associated to heat provision in a grid-connected situation.

1. Introduction

Over recent years, the rising demand for energy, due to rapid population and economic growth, as well as apprehensions associated with environmental problems, have raised concerns regarding the use of natural resources such as fossil fuels, natural gas, and liquid fuels [1]. This has led to calls for the introduction of new policies that will increase the use of renewable energy while reducing the use of fossil fuels [2, 3]. Renewable and environmentally friendly energy sources such as solar, wind, fuel cell, biomass, and biogas energy, are considered among the most advanced currently available energy sources [4]. In many developed and developing countries, much attention is paid to renewable energies, in order to diversify the energy resources, reduce the dependence on a specific energy carrier, and curb environmental problems, while maintaining a sustainable source of energy [5]. In comparison to the other renewable energy sources, solar energy is deemed the most favourable as it is abundant, cost-free, and pollution-free [6–8]. Over the past
ten years, the global market for photovoltaic systems has experienced rapid growth. The worldwide installation of photovoltaic systems climbed from 6GW in 2006, to 40GW in 2010, and to 505GW in 2018. Currently, renewable energy sources account for 26.2% of the total global energy generated, with 2.4% attributed to photovoltaic systems [9]. The International Energy Agency (IEA) anticipates an increase of 16% in the share of photovoltaic systems, by the year 2050 [8].

Potential locations for solar power plants include the United States in the southwest of the American continent, Mediterranean European countries, the deserts of Iran, India, Pakistan, Australia, and the Middle East, as well as the near east [10–14]. Energy production in the Middle East mainly involves the use of cheap fossil fuels. The demand for energy in this region has led to a production capacity that is close to maximum, and Iran is no exception to this trend. Iran’s gas reserves are second only to Russia, while its oil reserves are the fifth most significant worldwide. As such, Iran is considered one of the most energy-intensive countries in the world, with a per capita energy consumption 15 times that of Japan, and ten times that of the European Union. The substantial energy consumption in Iran, which is 3 times the world average, and 2.5 times the Middle East average, can be attributed to the allocation of subsidies for energy carriers. The constantly increasing energy consumption level in Iran has led to its global ranking of the nineteenth, in terms of energy production, and twentieth in terms of electricity consumption. Energy consumption in Iran is anticipated to increase by about 60% per year in the coming decades [14].

Accordingly, the energy sector has to direct its efforts toward meeting this ongoing demand. Rectifying the fossil fuel subsidy program [15], increasing the production capacity of nuclear power plants, generating tidal energy on the shores of the Persian Gulf [16], utilizing household and industrial waste, as well as installing wind and solar energy generators, are among the steps being considered by the Iranian government, to provide the required energy [14, 15].

Located on the world’s solar belt, Iran experiences 300 sunny days a year and an average of 2200 kWh/m² of solar radiation. As such, Iran has great potential when it comes to the exploitation of solar energy [14]. Currently, about 1% of Iran’s energy is derived from renewable energy sources, which, according to the 20-year development vision program, needs to expand to 10% by the year 2025 [17]. Figure 1, illustrates the contribution of solar energy, among different types of renewable energy sources in Iran. Currently, the total capacity of solar plant installations in Iran stands at 300 MW, which translates into 44% of its total renewable energy sources [18].

Similar to other renewable energy sources, solar energy generation performance is intermittent in nature, and the output power of photovoltaic panels is highly dependent on weather conditions. This issue often leads to the use of diesel generators, or batteries, as backup components alongside renewable energy sources, in order to increase their reliability [19–21]. However, the use of diesel generators comes with setbacks that include the frequent need for maintenance, a high degree of pollution, high noise, high fuel, and fuel transportation costs, as well as the need for multiple settings [22].

Although technology related to the use of batteries has developed considerably, a short lifespan (due to deep charging and discharging cycles), high replacement costs, poor performance under low temperatures and high pressures, the need for ventilation in some situations, and environmental issues related to the existence of toxic substances in their structure, occasionally render them inappropriate, particularly for long term energy storage [20, 23–25].

Hydrogen is one of the most efficient, cleanest, and lightest fuels, due to its high energy storing capacity [26]. Currently, the total global hydrogen production stands at approximately 50 million tons, with China heading the list with an annual production of 12.5 million tons. Of the total hydrogen production worldwide, almost 88% is linked to petrochemical industries, and the commercial sale of hydrogen is less than 10% of its production [27].

Hydrogen can be produced from a variety of sources, including crude oil and renewable energy. Currently, only 2% of hydrogen is derived from renewable energy sources. The use of renewable energy sources can be a suitable alternative for producing hydrogen. In this respect, water electrolysis, using photovoltaic systems, is among the best approaches for producing hydrogen, while maintaining a sustainable energy source [28]. As such, this undertaking focuses on the harnessing of solar energy, for the production of hydrogen.

One of the most frequently employed techniques, for maximizing the level of solar energy acquired, involves the use of the solar tracker [29, 30]. Currently, 27% of photovoltaic power plants around the world are equipped with solar tracking systems [17, 31]. In the context of Iran, this figure is roughly 10.5% (the 10 MW power plant in Qom, 10 MW power plant in Jarghooyeh, 10 MW power plant in Yazd, 1 MW power plant of Hamedan, and the 0.5 MW power plant in Shiraz).
As the production capacity of photovoltaic panels, is dependent on the amount of radiation they receive, the use of a tracking system, to constantly steer the surface of the panels, towards the direction of solar rays, will significantly enhance the power and efficiency of the panels [31]. However, the designing of solar trackers is usually a complicated affair, not to mention the high costs involved when it comes to the equipment required, and the implementation process. Thus, more often than not, the employment of these systems substantially raises the investment costs, for solar power plants. Over recent years, a variety of investigations have been conducted to address this issue [32–34].

Although the production of solar energy is widely discussed in the relevant literature, there are not many reports on the use of solar trackers. Taking this into consideration, this study delves into the effects arising from the use of different types of solar trackers, in a photovoltaic system, with an emphasis on hydrogen production. A review of the reports available in the literature, regarding renewable energy production, performed using the HOMER software, is presented in Table 1.

This undertaking represents the first investigation conducted in Iran, regarding the effect of single- and dual-axis solar trackers, on the amount of electricity, heat, and hydrogen produced simultaneously in a residential house, both off-grid and on-grid. Among the innovative approaches employed during this undertaking are the use of the Jask station 20-year average radiation data (acquired from NASA’s website), the use of a dump load for converting the excess electricity into heat, the use of heat recovery in fuel cell to produce both electricity and heat at the same time, the use of real data for three-phased electricity tariffs of Iran (including the penalty for pollutants discharged), and the reference to current costs with regards to equipment and infrastructure. Moreover, the results of the present work, the analyzing data method, and examining the simultaneous effect of the mentioned parameters make the originality of the work significant for researchers and decision-makers in the field of energy.

2. Geographic Location

Hormozgan province, with an area of 70697 km², lies to the south of Iran. The climate here is hot and humid, with temperatures soaring to as high as 49°C during summer. Jask, a city in the Hormozgan province, is located in the geographical coordinates of 25°64′ N and 57°77′ E. The geographical location of Jask is displayed in Figure 2. This Iranian city, with an area of 2161 km², is located 2 meters above sea level. The census report of 2017 recorded the population of Jask as 95,000. According to the study conducted by Jahangiri et al. [42], among the 103 stations established in Iran, the one with the most cost-effective solar system is located in Jask. Also, the Jask station is the only one that derives all its energy from renewable energy sources. No fossil fuels are involved in the operations of this station. Based on these facts, we opted for the city of Jask, for our case study.

3. HOMER Software

The hybrid optimization model, for electric renewables (HOMER) software, was developed by the National Renewable Energy Laboratory (NREL), Golden, Colorado, USA, for the feasibility study, of power systems that utilize renewable energy sources. HOMER is a computer model, which enables the designing of power systems, independent of, or connected to the power grid [43]. HOMER models the physical behaviour of an electricity generation system, and the cost of its lifetime, including the costs related to investment, replacement, as well as operations and maintenance. It allows the researcher to investigate various designs based on technical and economic criteria. Furthermore, this model enables an examination into the effects of data uncertainties and input changes, identified by the user, and provides the route towards the selection of the most professional and economical option. HOMER prepares a list of feasible optimal designs for the system, and sorts them based on their costs and economic efficiency. The HOMER analysis process necessitates the availability of information regarding the sources, economic constraints, and control methods. This software also requires inputs such as the type of equipment, their costs, the efficiency of the equipment, the lifetime of the system, and control methods. Additionally, HOMER comes with the capacity to perform sensitivity analysis for variables with uncertain values, and this sensitivity analysis can be conducted with a range of values, instead of a deterministic value. HOMER software is used for optimizing the performance strategy and size of the resources for renewable hybrid systems, based on three analysis modes: simulation, optimization, and sensitivity [43, 44].

HOMER uses the total net present cost (NPC) equation for calculating the lifetime costs, including the initial establishment cost, replacement cost, maintenance cost, fuel cost, electricity purchases from the grid, penalties for pollution, and the selling of electricity to the grid. In total NPC calculations, the costs are considered positive, and the revenues considered negative. HOMER simulates all possible cases (except for impractical cases), and then sorts them based on total NPC, to eventually identify the feasible arrangement with the least total NPC, as the optimal arrangement. Total NPC is calculated as follows [26]:

$$\text{total NPC} = \frac{C_{\text{ann}}^{\text{tot}}}{\text{CRF}(i, R_p)},$$

where $C_{\text{ann}}^{\text{tot}}$ represents the total annual costs, $i$ is the annual interest rate (money discount rate), $R_p$ denotes the lifetime of the project, and CRF denotes the capital return coefficient, which is calculated by way of the following equation [26]:

$$\text{CRF}(i, N) = \frac{i(1 + i)^N}{(1 + i)^N - 1}.$$
| Ref. | Year | Study area         | Grid       | Load (kWh/d) | Design                | NPC ($) | COE ($/kWh) | COH ($/kg) | Dump load | Heat recovery | Solar tracker |
|------|------|--------------------|------------|--------------|-----------------------|---------|-------------|------------|-----------|---------------|--------------|
| [23] | 2019 | South Africa Cape Town | Off-grid   | 1200         | PV-FC-EL-HT-SP        | 26626630 | 4.78        | —          | No        | No           | No           |
| [35] | 2019 | Iran Hormozgan      | On-grid    | 13.9         | EL- RE-HT             | 84200   | 3.036       | 0.496      | No        | No           | No           |
| [26] | 2019 | Chad                | On-grid    | 14           | EL- RE-HT             | 2413770 | 28.710      | 4.695      | No        | No           | No           |
| [28] | 2019 | Iran Tabriz          | Off-grid   | 70           | PV-FC-EL-HT- batt     | 192338  | 0.286       | —          | No        | No           | No           |
| [20] | 2019 | Egypt Minya          | On-grid    | 110          | PV-FC-EL-HT           | 391690  | 0.206       | —          | No        | No           | No           |
| [24] | 2019 | Italy Reggio Calabria | Off-grid   | —            | PV-FC-EL-HT           | 24000   | 0.87        | —          | —         | —            | Yes          |
| [21] | 2020 | Iran Chaldoran       | Off-grid   | 361          | PV-BG-FC-RF-HT-batt   | 444605  | 0.225       | —          | No        | No           | No           |
| [25] | 2020 | Turkey Mumcular dam  | Off-grid   | 499          | PV-FC-EL-HT           | 581733  | 0.6124      | —          | No        | No           | No           |
| [36] | 2021 | India Karnataka      | No         | 724.83       | PV-WT-BG-FC-EL-HT     | 890013  | 0.214       | —          | No        | No           | No           |
| [37] | 2021 | Malaysia Kedah       | Yes        | 20000        | PV-FC-EL-HT-batt      | -38.2M  | -0.409      | —          | No        | No           | No           |
| [38] | 2022 | India Nalanda        | Yes        | 1010.8       | PV-WT-FC-DG-EL-HT-batt-ref | 378000  | 0.088       | —          | No        | No           | No           |
| [39] | 2022 | Oman Duqm            | Yes        | 827061       | PV-WT-FC-EL-HT-batt   | 1.53 B  | 0.322       | —          | No        | No           | No           |
| [40] | 2022 | Iran All provinces   | Yes        | 480          | PV-EL-HT              | —       | —           | —          | No        | No           | No           |
| [41] | 2022 | Iran East Azarbijan  | No         | —            | WT-EL                 | —       | 0.045       | 1.38       | No        | No           | No           |
| Present work | 2022 | Iran Jask            | Yes        | 5.9          | PV-WT-FC-EL-HT-batt   | 9321    | 0.116       | 29.33      | Yes       | Yes          | Yes          |

PV: Photovoltaic; WT: Wind Turbine; FC: Fuel Cell; EL: Electrolyzer; RE: Reformer; HT: Hydrogen Tank; BG: Biogas Generator; DG: Diesel Generator; SP: Supercapacitor; HP: Hydro Power; Ref: Reformer.
COE = \frac{C_{\text{ann}}}{E_{\text{served}}} \tag{3}

where $E_{\text{served}}$ represents the actual cost of electric load in kWh/yr.

HOMER software uses the following equation to calculate the output power of photovoltaic cells [47]:

$$P_{\text{pv}} = Y_{\text{pv}} f_{\text{pv}} \left( \frac{G_{T}}{G_{\text{STC}}} \right) \tag{4}$$

where $Y_{\text{pv}}$ is the standard output power of the solar cell in kW, $f_{\text{pv}}$ denotes the derating factor, $G_{T}$ depicts the radiation absorbed by the cell’s surface each month in kW/m², and $G_{\text{STC}}$ is the amount of radiation absorbed by the cell in standard conditions in 1kW/m².

Using the power curve and wind speed at the hub height, the HOMER software calculates the output power of wind turbines through the following equation [48]:

$$P_{\text{WTG}} = \frac{\rho}{\rho_0} \times P_{\text{WTG,STP}} \tag{5}$$

where $\rho$ is the actual air density in terms of kg/m³, $\rho_0$ is the air density in standard temperature and pressure conditions, which is equal to 1.225, and $P_{\text{WTG,STP}}$ denotes the output power of the wind turbine in standard temperature and pressure conditions.

At each time step, the HOMER software calculates the maximum power the battery can receive. This maximum power at each time step will be different, depending on the current charge percent of the battery, its discharge history, and so on. The software imposes three constraints on the maximum battery capacity. $P_{\text{batt,max,km}}$ is related to the kinetic battery model, $P_{\text{batt,max,mcr}}$ is related to the battery’s maximum charging rate, and $P_{\text{batt,max,mcc}}$ is related to its maximum charging current. The HOMER software then considers the minimum of these three values the maximum power [49]:

$$P_{\text{batt,max}} = \min\left( P_{\text{batt,max,km}}, P_{\text{batt,max,mcr}}, P_{\text{batt,max,mcc}} \right) / \eta_{\text{batt,c}} \tag{6}$$

where $\eta_{\text{batt,c}}$ represents the charging efficiency of the battery.

Subsequent to entering the fuel curve for the fuel cell, the HOMER software proceeds to plot its corresponding efficiency curve. The equation for electrical efficiency of the fuel cell is expressed as follows [50]:

$$\eta_{\text{gen}} = \frac{3.6 \cdot P_{\text{gen}}}{m_{\text{fuel}} \cdot \text{LHV}_{\text{fuel}}} \tag{7}$$
where \( P_{\text{gen}} \) is the output electricity in terms of kW, \( \text{LHV}_{\text{fuel}} \) represents the low heating value of the fuel in terms of MJ/kg and, \( m_{\text{fuel}} \) represents the fuel consumption of the generator per hour.

The inverter’s efficiency factor is defined as the percentage of DC electricity it converts to AC electricity. The rectifier’s efficiency factor, on the other hand, is defined as the percentage of AC electricity it converts to DC electricity. It should be noted that the HOMER software assumes the efficiency factors of the inverter and rectifier to be constant [51].

The modelling of a system, that generates its required hydrogen by electrolyzing its excess electricity, necessitates the existence of a hydrogen tank, to store hydrogen for consumption by the fuel cell. The autonomy of the hydrogen tank is defined as the ratio of the hydrogen tank’s energy capacity to its electric charge. This is calculated as follows [52]:

\[
A_{\text{tank}} = \frac{Y_{\text{tank}} \times \text{LHV}_{\text{H2}} (24\text{h/d})}{L_{\text{prim.ave}} (3.6\text{MJ/kWh})},
\]

where \( Y_{\text{tank}} \) denotes the nominal capacity of the hydrogen tank in terms of kg, \( \text{LHV}_{\text{H2}} \) denotes the low heating value of the hydrogen fuel (120(MJ/kg)), and \( L_{\text{prim.ave}} \) is the average primary charge in terms of kWh/day.

The electrolyser efficiency is defined as the amount of electricity which is converted to hydrogen, and is equal to the energy content of hydrogen in terms of high heating value divided by the amount of electricity consumed.

If the net electricity generation is calculated on a monthly basis, the HOMER software calculates the total annual cost of energy by way of the following equation [53]:

\[
C_{\text{grid energy}} = \sum_{i=1}^{\text{yrates}} \sum_{j=1}^{12} \begin{cases} E_{\text{net grid purchases.} \, i,j} \times \text{c}_{\text{power.} \, i} & \text{if } E_{\text{net grid purchases.} \, i,j} \geq 0 \\ E_{\text{net grid purchases.} \, i,j} \times \text{c}_{\text{sellback.} \, i} & \text{if } E_{\text{net grid purchases.} \, i,j} < 0 \end{cases}.
\]

In this equation, the parameters \( E_{\text{net grid purchases.} \, i,j} \), \( \text{c}_{\text{power.} \, i} \) and \( \text{c}_{\text{sellback.} \, i} \) denote the net purchase of the \( j \)-th month when the rate \( i \) is applied, the price of electricity for the rate \( i \), and the price of selling electricity to the grid with the rate \( i \), respectively.

HOMER software is an optimization software and as shown in Figure 3 [54], it can be used to check the various configurations and perform technical, economic, and environmental analyses. Its output results highly depend on input parameters. This software is a tool that can be used anywhere in the world. In this study the climatic and geographical data, electricity exchange with the grid, real interest rate, and other parameters are considered for Iran, so the results of the present work are very accurate in accordance with the reality in Iran.

4. Required Data

A schematic diagram of the systems under investigation is provided in Figures 4(a) and 4(b). As can be gathered from Figure 5(a) [47] and Figure 6(a) [55], the most important data inputs of the software, are the amount of electricity and heat required, during a period of 24 hours. The software uses random variables to convert daily data into annual data, which are hour-by-hour and time-step-by-time-step, and are assumed to be equal to 15% and 20%, respectively, for this undertaking. The application of these variables give rise to Figure 5(b) and Figure 6(b), which depict the electricity and heat required for the entire year, respectively.

In this study, a dump load is used to convert excess electricity into heat. This is portrayed in Figure 4. A dump load (or electric boiler) is, in fact, a resistive heater that converts excessive electricity, which cannot be stored in the battery, into heat.

The use of solar cells and wind turbines necessitates the access to data, relating to the amount of solar radiation and wind velocity, at the station under study. These data, which represent 20-year averages, were obtained from NASA’s website [56], and are depicted in Figures 7(a) (global horizontal radiation) and 7(b) (wind speed). Based on these data, the average annual solar radiation and wind speed at the Jask station were computed as 6.18 kWh/m²-day, and 4.07 m/s, respectively.

Considering the fuel consumed by the boiler to be diesel, the price of each litre of diesel was assumed to be 0.02 $ during the calculations [57]. In order to assess the impact of the cost of the \( \text{CO}_2 \) pollutant penalty on the system costs, it was assumed to be 35$ per ton [58]. Also, the actual annual interest rate was assumed to be 18% [59]. Table 2 provides the technical information, and the price of the equipment used during this undertaking.

The prices used in the present work are not only specific to Iran because the equipment evaluated in this research is easily available and can be purchased in most countries. It should be noted that according to the use of electricity consumption prices and climate data in Iran, the results of the present work are specific to Iran, but the method of work and the method of analysing the results can be used anywhere in the world.

The system comes with the capacity to connect to the national electricity grid, and to exchange electricity with the grid. This facilitates the investigation, on the impact of connection to the national electricity grid, on the costs.
As illustrated in Figure 8, taking into consideration the differing price of electricity during off-peak, peak, and normal hours, three plans were used for exchanging electricity with the grid in Iran. The purchase and sale prices of electricity were assumed to be the same, and this explains why the prices are set as 0.12, 0.07, and 0.05 $/kW hours, for
Figure 6: Thermal load (a) Daily profile, and (b) Yearly profile.

Figure 7: Yearly resources (a) Global horizontal radiation, and (b) Wind speed.

Table 2: Technical information and the price of equipment used.

| Component        | Capital Cost ($) | Replacement Cost ($) | Operation and maintenance Cost ($) | Specifications                                      |
|------------------|------------------|----------------------|------------------------------------|-----------------------------------------------------|
| PV No-track [60] | 1250             | 1505 2121            | 1125 1355 1909                     | Lifetime: 25 years Derating factor: 80%             |
| PV HACT [60]     | 2275             | 2275                 | 2275                               |                                                     |
| PV TACT [60]     | 2048             | 2048                 | 2048                               |                                                     |
| Wind turbine [61]| 5000             | 4000                 | 50                                 | Type: WES 5 Tulipo Rated power: 2.5 kW AC lifetime: 25 years Hub height: 25 m Cut-in speed: 2 m/s |
| Battery [61]     | 1200             | 1100                 | 50                                 | Type: Surrette 6CS25P Lifetime: 9645 kWh            |
| Converter [45]   | 300              | 300                  | 0                                  | Inverter efficiency: 95% Rectifier efficiency: 95% |
| Fuel cell [20]   | 3000             | 2500                 | 0.02                               | Lifetime: 40000 h Min. Load ratio: 25% Efficiency: 90% Heat recovery ratio: 25% |
| Electrolyzer [20]| 500              | 250                  | 10                                 | Lifetime: 20 years Min. Load ratio: 0% Efficiency: 85% |
| Hydrogen tank [45]| 574             | 574                  | 10                                 | Lifetime: 25 years Initial tank level: 20%         |
| Boiler [50]      | —                | —                    | —                                  | Efficiency: 85% Carbon monoxide 6.5 g/L Unburned hydrocarbons 0.72 g/L Particulate matter 0.49 g/L Fuel sulfur converted to PM 2.2% Nitrogen oxides 58 g/L |
peak, normal, and off-peak hours, respectively. Additionally, as CO$_2$ is recognized as the main pollutant, 632 grams of CO$_2$ is assumed to be produced per kWh of electricity generated in the national grid. The purchase and sale capacity, of electricity from/to the national power grid, is assumed to be 2000 kW.

5. Simulation Results

5.1. Disconnected from the Grid Condition. Results from investigations on the most economical situation for the simultaneous generation of electricity, heat, and hydrogen in the station under study, under the circumstance of being disconnected from the national electricity grid, are displayed in Table 3. These results reveal that the use of solar cells complements the use of wind turbines in all scenarios, and optimal systems comprise only of solar cells.

According to Table 3, in the scenario without a tracker, three solar cells are required, while in the scenario with a tracker, two solar cells are required. Put plainly, electricity generation through solar cells, in the scenario without a tracker, is more than in the scenario where a tracker is involved. The most cost-effective scenario for the simultaneous generation of electricity, heat, and hydrogen, is the one involving the use of a vertical tracker, with a total price of 0.8125/ kWh of energy produced, which has the total NPC of $9998. The highest and lowest percentages of renewable energy used are for the scenario without a solar tracker (55.3%), and the scenario with a vertical tracker (49%), respectively. The results also revealed that the scenario involving the use of a horizontal axis tracker, which is the most expensive system among the scenarios under investigation (Table 3), consumed the most amount of diesel (557 L/y) to generate heat. This is attributed to the fact that the generation of the least amount of electricity, is associated to solar cells, and the generation of the most amount of electricity, is associated to fuel cells.

The issue of excess electricity stems from the circumstance, that the system is not connected to the grid. The highest and lowest amounts of electricity were generated in the scenario without a tracker (2596 kWh/y), and the scenario with a vertical axis tracker (975 kWh/y), respectively. It is notable that in the context of required heat generation, in the scenario without a tracker, where a high amount of excess electricity is generated, the provision of heat through the dump load led to the generation of excess heat, to the tune of 532 kWh/y. This represents the highest amount of excess heat generated, among the cases under study. However, as can be observed in Table 3, most of the heat was generated by way of the boiler.

The scenario with a double axial tracker delivered the most solar cell operation hours (5402 hours), while the scenario with a horizontal axis tracker delivered the most prolonged fuel cell operation hours. This prolonged fuel cell operation hours associated to the use of a horizontal axis tracker, is attributed to the higher amounts of hydrogen generated by the electrolyser.
Table 3: The results of different scenarios in the case of not connected to the grid.

| Scenario   | Component                  | Total NPC ($) | COE ($/kWh) | Ren. Frac (%) | Diesel (L) | Elec. Prod (kWh/y) | Exc. Elec (kWh) | Therm. Prod (kWh/y) | Exc. Therm. (kWh) | Operation (h) | H₂ prod. (kg/y) | CO₂ (kg/y) | LCOE ($/kWh) | LCOH ($/kg) |
|------------|----------------------------|---------------|-------------|---------------|-------------|-------------------|----------------|---------------------|----------------|---------------|-----------------|-------------|-------------|-------------|
| No Track   | PV (3), FC (1), Batt (1), Conv. (1), Elec. (1), H₂ tank (1) | 10442         | 0.849       | 55.3          | 418         | PV (5862) FC (412)| 2596           | FC (99) Boil. (3495) Dump load (2596) | 532           | 24.5          | +1100          | 0.12        | 77.968      |
| VACT       | PV (2), FC (1), Batt (1), Conv. (2), Elec. (1), H₂ tank (1) | 9998          | 0.812       | 49            | 480         | PV (4847) FC (356)| 1706           | FC (48) Boil. (4011) Dump load (1706) | 144           | 20.8          | +1263          | 0.116       | 87.743      |
| HACT       | PV (2), FC (1), Batt (1), Conv. (2), Elec. (2), H₂ tank (1) | 11893         | 0.972       | 40            | 557         | PV (4264) FC (439)| 975            | FC (104) Boil. (4659) Dump load (975) | 80.3          | 25.7          | +1467          | 0.186       | 84.654      |
| TAT        | PV (2), FC (1), Batt (1), Conv. (2), Elec. (1), H₂ tank (1) | 11534         | 0.942       | 54.8          | 422         | PV (5403) FC (340)| 2278           | FC (80) Boil. (3532) Dump load (2278) | 232           | 20.2          | +1112          | 0.157       | 104.577     |
Table 4: The results of different scenarios in the case of being connected to the grid.

| Scenario | Component               | Total NPC ($) | COE ($/kWh) | Ren. Frac (%) | Diesel (L) | Elec. Prod (kWh/y) | Therm. Prod (kWh/y) | Operation (h) | H₂ prod. (kg/y) | CO₂ (kg/y) | LCOE ($/kWh) | LCOH ($/kg) | Grid (kWh) |
|----------|-------------------------|---------------|-------------|---------------|------------|-------------------|--------------------|---------------|-----------------|------------|--------------|-------------|------------|
| No Track | PV (1), WT (1), FC (1), Batt (1), Conv. (1), Elec. (1), H₂ tank (1) | 10928 | 0.277 | 54 | 663 | PV (1954) | WT (5872) | FC (1615) | Grid (212) | 54.7 | -1139 | PV (0.12) | 36.54 | Purch. (212) | Sold (4774) |
| VACT     | PV (1), WT (1), FC (1), Conv. (1), Elec. (1), H₂ tank (1) | 9321 | 0.223 | 56 | 662 | PV (2423) | WT (5872) | FC (1719) | Grid (196) | 58.1 | -1358 | PV (0.116) | 29.33 | Purch. (196) | Sold (5145) |
| HACT     | PV (1), WT (1), FC (1), Conv. (1), Elec. (1), H₂ tank (1) | 10180 | 0.256 | 55 | 661 | PV (2132) | WT (5872) | FC (1826) | Grid (202) | 61.7 | -1172 | PV (0.186) | 30.17 | Purch. (202) | Sold (4809) |
| TAT      | PV (1), WT (1), FC (1), Conv. (1), Elec. (1), H₂ tank (1) | 9914 | 0.228 | 57 | 662 | PV (2702) | WT (5872) | FC (1662) | Grid (195) | 56.1 | -1575 | PV (0.157) | 32.3 | Purch. (195) | Sold (5446) |
In terms of CO₂ emissions over the period of one year, the scenario with a horizontal axis tracker, with a CO₂ emission of 1467 kg, is deemed the most inappropriate, while the scenario without a solar tracker, with a CO₂ emission of 1100 kg, is considered the most appropriate.

Another issue that needs to be considered is the levelized cost of each kg of generated hydrogen, or each kWh of generated energy (Table 3). According to the results, the lowest price for each kg of generated hydrogen ($77.97), corresponds to the scenario without a tracker, while the lowest price for every kWh of produced energy ($0.116), corresponds to the scenario involving the use of a vertical axis tracker.

5.2. Connected to the Grid Condition. The results derived for different scenarios, regarding the use of different types of solar trackers, under the circumstance of being connected to the national electricity grid, are presented in Table 4. According to these results, the equipment for all three scenarios with a tracker is similar, and only the scenario without a solar tracker requires an additional backup battery.

As can be gathered from the results, the lowest price for each kWh of produced energy ($0.223), is associated to the scenario with a vertical axis tracker. The most inappropriate economic scenario, with a total NPC of $10928 and 0.227 $/kWh produced energy, is the scenario without a tracker. The use of a two-axial tracker was the most appropriate scenario, with a 57% demand satisfaction ratio via renewable energies, and the scenario without a tracker, provided the least demand satisfaction with a ratio of 54%.

Based on the results exhibited in Table 4, it can be surmised that the operating hours of the solar cell, wind turbine, and boiler are similar. This can be put down to the constant diesel fuel consumption, and the constant value of electricity produced by the wind turbine in all scenarios. The most and least amounts of electricity produced by the solar cell are associated to the scenario with a dual axial tracker (2702kWh/y), and the scenario without a tracker (1954 kWh/y), respectively. The greatest amount of hydrogen produced (61.7kg/y), which is due to the highest performance of the electrolyzer with 4768 hours, is associated to the scenario with a horizontal axis tracker.

Also apparent in Table 4, is that while the heat providing role of the dump load is robust, in the circumstance of the system being disconnected from the grid, it does not come into play, when the scenarios under consideration are connected to the national electricity grid. This is attributed to the fact that it makes more business sense to sell the excess electricity to the grid, than to go through the process of converting it into heat.

Interestingly, the results displayed in Table 4, also revealed that the amount of pollutant emissions is negative for all the situations considered. This is an indication that the quantity of electricity sold to the grid, is greater than the electricity purchased from it. Such a situation serves to inhibit the emission of pollutant gases. The highest rate of CO₂ pollutant emission prevention at 1575 kg/year is claimed by the scenario with the dual-axis tracker.

Due to the similarity in performance of the wind turbine for all the situations considered, the levelized price for each kWh, of the wind electricity produced, is the same for all scenarios, i.e. $0.174. The lowest and highest price of solar electricity produced are associated to the scenario with the vertical axis tracker ($0.116 $/kWh), and the scenario with the horizontal axis tracker ($0.186 $/kWh), respectively.

6. Achievements and Future Works

The simultaneous production of electricity, heat, and hydrogen is an approach that results in increasing the efficiency of energy systems and has received very little attention in Iran. Considering the importance of using excess electricity and converting it into heat, as well as providing hydrogen as a clean fuel, the results of the present work can lead to the development of the use of this type of system in Iran. For more works resulting from this article, other renewable energy sources such as biomass, geothermal, etc. can be used instead of wind and solar energies. It is also possible to rank the use of these systems in different parts of the country by using existing software and numerical methods. It is also possible to draw GIS maps and make it easier for energy field managers to make macro-decisions.

7. Conclusions

The geographical location of Iran is conducive for the replacement of fossil fuels with solar energy. However, among the stumbling blocks to this realization, is the poor efficiency of solar cells. In order to improve the efficiency of these cells, single and dual-axis solar trackers can be applied. The focus of this research is on hydrogen production and the effects of using the solar tracker on energy, environment, and economic parameters in the Jask, Iran. It should be noted that the present work is a trigeneration (production of electricity, heat, and hydrogen) that has not been done in previous studies. Therefore, the results of this study can be used for other places with similar climates and be a road map for decision-makers in the field of energy. Also, the used method and analysis of the results can be used for any other part of the world with any climate. Four scenarios (without a solar tracker, with a horizontal axis tracker, with a vertical axis tracker and with a dual axis tracker) were subjected to energy-technical-economic-environmental evaluations via HOMER software. The originality of this undertaking is defined by (a) the use of a solar tracker at the best station in Iran [47], (b) the use of real three-phase electricity tariffs data, (c) the use of dump load for the generation of the required heat, (d) analysis based on up-to-date prices of equipment, (e) the consideration of penalties for pollutants produced, and (f) the use of heat recovery in fuel cell. The main results derived through this investigation are as follows:

For the off-grid situation:
(i) The vertical axis tracking system generates the cheapest electricity, at the price of 0.116 $/KWh
(ii) The system without a solar tracker produces the cheapest hydrogen, at the price of 77.97 $/kg
(iii) The role of the dump load is significant, when it comes to providing the required heat
(iv) The system with a horizontal axis tracker, is the most inappropriate choice both economically and environmentally

For the on-grid situation:
(i) The generation of the cheapest energy (0.223 $/kWh), is attributed to the scenario with the vertical axis tracker
(ii) The cheapest hydrogen production (29.33 $/kg) is associated to the scenario with a vertical axis tracker
(iii) The dump load does not play any role in the provision of required heat
(iv) The highest percentage of renewable energy usage (57%) is associated to the scenario with a dual-axis tracker

Data Availability
All data used to support the findings of this study are included within the article.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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