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# Finding The Best Configuration of an Off-Grid PV-Wind-Fuel Cell System with Battery and Generator Backup: A Remote House in Iran

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**Abstract**

One of the most important indicators of sustainable rural development is energy supply. Therefore, the present work has been done with the aim of identifying the potential of wind, solar and fuel cell (FC) energy in the electricity supply of Tamin village located in Sistan and Baluchistan province by HOMER 2.81 software. Different scenarios were investigated and diesel generators (DGs) and batteries were used as systems backup. The present work is the first renewable hybrid project based on a FC for a remote area in one of Iran's climates, and accurate and up-to-date technical, economic, energy and environmental analyzes have made the results very important. The results of the investigations showed that the DG-Wind turbine system is the cheapest system with the price of each kWh of electricity produced equal to $0.735. The FC-based system also significantly reduces production pollutants at a cost of $1.004 per kWh of electricity produced and uses 53% more renewable energy than the superior economic scenario. The production of hydrogen for use in a FC during the year is equal to 50.7 kg, and compared to the traditional system (DG only), the FC-based system has a payback time of 3.43 years.

**Keywords:** Rural area, $CO_2$ emission, HOMER software; 3E analysis

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## 1. Introduction

It is estimated that by 2035, the world's population will exceed 8.7 billion people, which means that an additional 1.6 billion people will need energy [1]. The main problem is the increase in energy demand and the decrease in fossil fuel supply, along with the issues related to the implementation of traditional fossil fuels on human health [2, 3]. There is an urgent need to use green and sustainable alternative energy to replace existing non-renewable fossil fuels [4, 5]. It is noted that the production of renewable energy has increased globally [6, 7]. According to the surveys, at the end of 2020, the global renewable energy production capacity reached 2799 GW [8]. At the end of 2013 and 2004, this capacity was equal to 1560 and 895 GW, respectively [9]. Hydropower plants with 1211 GW and wind and solar energy with a capacity of 733 GW and 714 GW, respectively, have taken the largest share of the total global production. Other renewables include 127 GW of bioenergy and 14 GW of geothermal energy, plus 500 MW of marine energy (Figure 1).

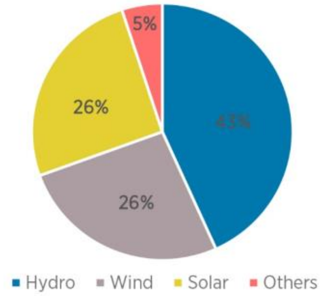


Figure 1. Renewable energy production capacity from different energy sources [8]

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Iran has a high ability to establish all kinds of renewable energy sources and implement efficient energy systems [10-12]. According to the latest statistics of Iran's Renewable Energy and Energy Efficiency Organization (SATBA) (Figure 2), at the end of 2021, out of 904.07 MW of renewable electricity, the largest share was related to solar and wind sectors [13]. According to the roadmap shown in Table 1, Iran plans to produce more than 2000 MW of electricity from renewable energy by 2027.

Table 1. Development of renewable energy capacity in Iran until 2027 [14]

| Type of Technology | Capacity (MW) |
|---|---|
| Wind energy | 1600 |
| Biomass energy | 130 |
| Geothermal energy | 100 |
| FC | 90 |
| Photovoltaic energy | 40 |
| Solar thermal energy | 40 |
| Total | 2000 |

However, renewable power plants have been reported to have many disadvantages [15, 16]. One of the disadvantages is that renewable power plants are usually located far from the point of demand, which causes problems in the transmission of renewable energy [17, 18]. Integrating renewable energy technologies into a single system to meet the electrical demand of remote locations can be more reliable [19]. One of these new integration technologies is FC technology, which offers a quick solution to the problems mentioned above [20, 21]. With the increase in demand for renewable energy sources, the FC is a very efficient, clean and sustainable source of energy conversion [22]. FCs have the potential for various applications, such as portable power, stationary electricity generation, vehicle propulsion, and in large electric power plants [23, 24]. The global FC market size is projected to reach $848 million by 2025, from an estimated value of $263 million in 2020.

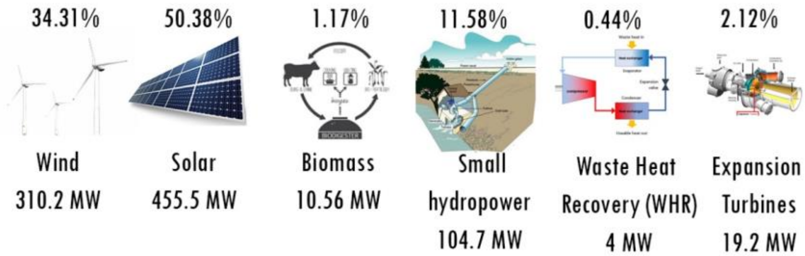


Figure 2. The share of renewable power plants from 904.07 MW of renewable electricity in Iran until the end of 2021 [13]

In Iran, the main custodian of renewable energy exploitation is SATBA, and the most important activities of this organization in the field of FC technology policy are:

- Conducting baseline studies (feasibility assessment, attractiveness analysis and formulation of FC technology development strategy in Iran)
- Compilation of the national strategy document for the development of FC technology
- Compilation of the operating plan of the FC certificate and its actions in accordance with the national innovation system
- Supporting postgraduate theses in the field of hydrogen and FC
- Determining the tariff and including FC electricity in the system of guaranteed renewable electricity purchase contracts

Electrification of villages is a vital step to improve the technical and economic conditions of rural areas [25, 26]. In 2020, about 850 million people worldwide still face insufficient access to electricity, most of whom live in rural areas of developing countries [27]. Many rural areas of Iran still do not have access to electricity, it seems that expanding the existing electricity grid to meet their electricity needs is economically and technically impossible. On the one hand, these populations are remote, scattered and characterized by low electricity consumption, and on the other hand, most of them are very poor and unable to pay electricity bills. In this case, independent power systems can provide the best alternative compared to the construction and operation of new power grid lines. In this study, a solar-wind-FC technology is modeled and simulated to determine whether this configuration can be suitable for a household located in rural Iran.

Table 2 shows the literature review of recent studies on the use of renewable energy in remote areas. Based on the studies conducted in Table 2, no detailed and comprehensive investigation has been done regarding electricity supply at the rural scale with scenarios based on renewable energy for remote areas in Iran. In addition to the fact that there is no equivalent for the present work in terms of geographical location, the use of new technical and price data for the equipment used makes the results more consistent with reality. This issue can be significant for the decision-makers and investors in developing renewable energy at the rural scale. Although the present work is a case study, the method of doing the work and the way of analyzing the results can be used for any other climate.

Table 2. Literature review of studies conducted in the field of electrification in remote areas with and without FCs

| Ref. | The problem under consideration | Methodology | Result |
|---|---|---|---|
| [28] | PV/FC/battery/electrolyzer hybrid power generation system with 80 kW PV and 10 kW FC for remote areas for agricultural applications in India | HOMER | COE equal to 0.431 $/kW |
| [29] | Techno-economic analysis of a hybrid PV/wind/FC power generation system consisting of 110 kW PV, one PGE 20/25 wind turbine, one 40 kW inverter, 120 Surrette S6CS25P batteries, one 5 kW fuel cell, 25 kW electrolyzer and 15 kg hydrogen tank for a village in Ethiopia | HOMER | COE equal to 0.313 $/kW |
| [30] | Technical-Economic Study of a Hybrid PV/Wind/FC System for a Remote Area Located in Beni-Suef Province in Egypt | The Firefly Algorithm (FA) and the Shuffled Frog Leaping Algorithm (SFLA) and the particle swarm optimization (PSO) | The simulation results showed that the combination of PV/wind/FC combined with an electrolyzer for hydrogen production provides excellent performance. The proposed system is economically viable with an energy cost of $0.47/kWh. |
| [31] | Investigating the prospect of choosing an energy system consisting of wind turbines, PV, FC, electrolyzer, hydrogen storage and battery energy storage to supply residential load energy in Lagos, Nigeria. | HOMER and ranking of energy systems using complex proportional assessment | Battery- PV was ranked the best using a single criterion. The PV-wind turbine-FC-battery hybrid combination received the best rating based on multiple criteria. |
| [32] | Investigating electricity generation based on multiple HRES combinations at an off-grid rural location in India. | HOMER | A combination of PV-Wind-Biomass-Biogas-FC with battery was identified as the cheapest and most reliable solution with a COE of $0.214/kWh. |

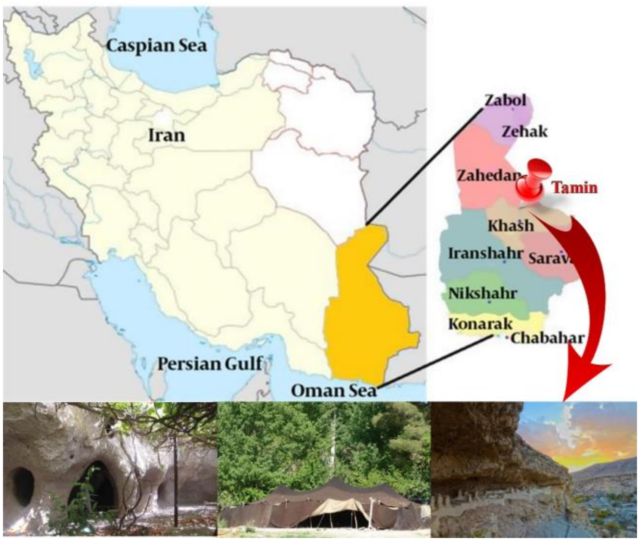


Figure 3. The location of the investigated place on the map of Iran.

## 2. The place under study

As shown in Figure 3, the investigated location is Tamin village in Taftan city of Sistan and Baluchistan province. This village is of interest to tourists due to its special features and unique nature. Due to its geographical location and its proximity to Mount Taftan, this village has a cool climate and many springs [33].

## 3. Used software

HOMER is a software that has the task of designing small power generation systems based on renewable energies in off-grid and on-grid modes [34]. The size of the equipment, the selection of each piece of equipment, technical, economic, environmental calculations, etc. are selected by the software [35]. Performing sensitivity analysis and using optimization algorithms make it easy to evaluate systems [36]. The performance diagram of HOMER software is shown in Figure 4 [37]. As seen in Figure 4, at first, HOMER receives the inputs from the user. These inputs include the electricity consumed 24 hours (hour by hour), average monthly data of solar radiation and wind speed, capital, replacement, and maintenance costs of equipment, annual inflation rate, the lifetime of the project, diesel price, and the amount of DG pollutants. Then calculations are done and the results are ranked according to the lowest NPC value. Based on the various configurations that HOMER software checks based on the size of the equipment, calculations will be made and finally, the lowest total NPC of each configuration will be included in the HOMER output results list.

## 4. System under study

As seen in Figure 5, the investigated system includes a solar cell, FC, hydrogen tank, wind turbine, electric converter, DG, and battery, which must provide 15 kWh/day of daily electricity with a peak of 1.7 kW. The price of one liter of diesel is equal to 0.011 $ [38], the annual interest rate is 18% [39] and the wind speed and solar radiation data are 25-year average and were extracted from the NASA website [40]. Figures 6 to 8 show the required electricity profile, solar radiation, and annual wind speed of the under study station, respectively.

Table 3 shows the price, technical and other information of the investigated system. It should also be noted that the penalty for pollution in Iran is zero dollars, and therefore, no fine has been considered for DG emissions in the present work [41].

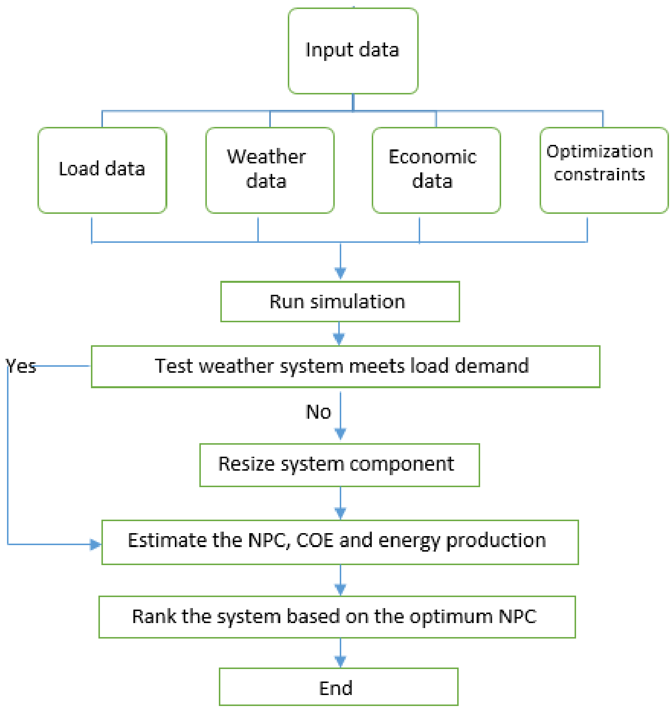


Figure 4. Schematic diagram of HOMER software performance [37]

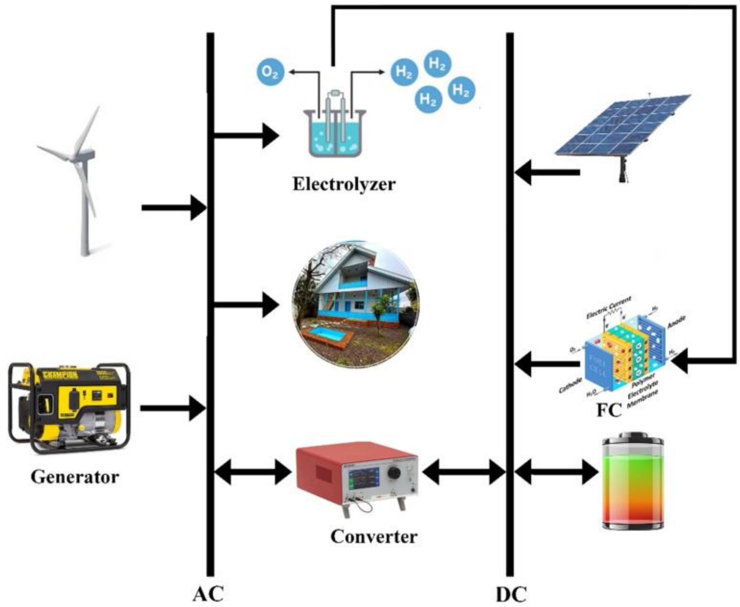

Figure 5. Schematic of under study system

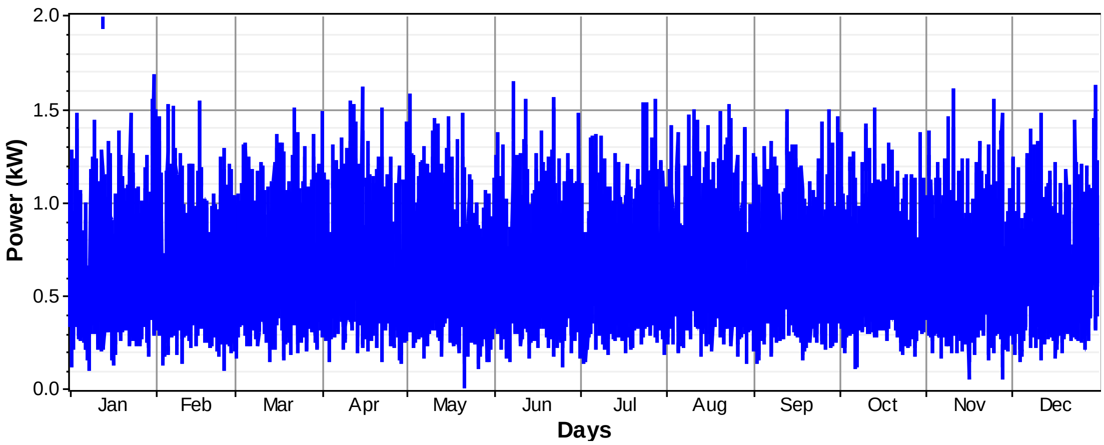

Figure 6. Electricity daily profile

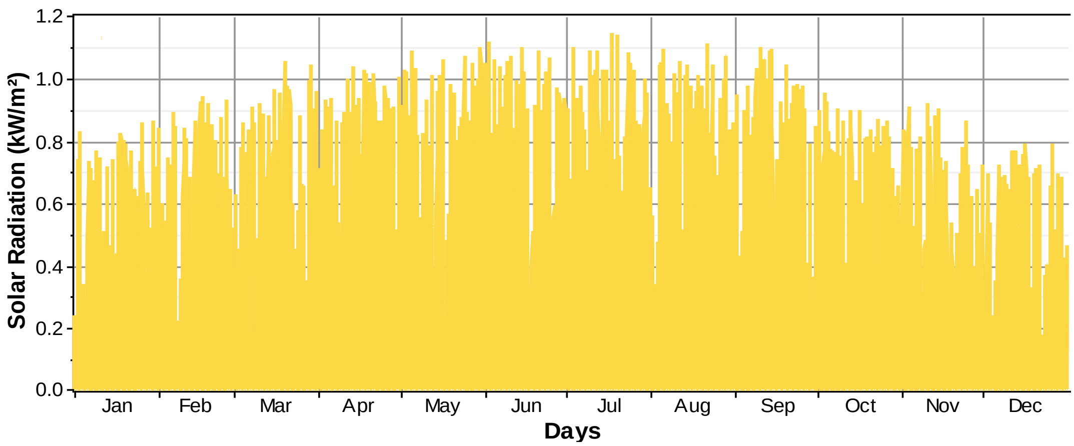

Figure 7. Daily solar radiation profile

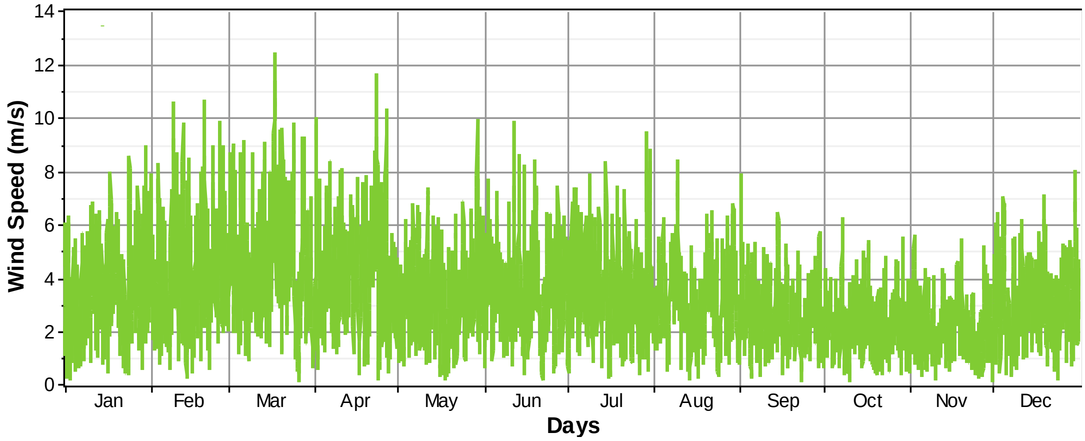


Figure 8. Daily wind speed profile

Table 3. Specifications and price of equipment

| Component | Cost ($) | | | Specifications | Size to consider (kW) |
|---|---|---|---|---|---|
| | **Capital** | **Replacement** | **Operation and maintenance** | | |
| PV [42] | 2000 | 2000 | 10 | Lifetime: 25 years<br>Derating factor: 80%<br>Slope: 28.11° | 0-15 |
| Wind turbine [43] | 5000 | 4000 | 50 | Type: WES 5 Tulipo<br>Rated power: 2.5 kW AC<br>Lifetime: 15 years<br>Hub height: 25 m<br>Cut-in speed: 2 m/s | 0-3 |
| Battery [44] | 1200 | 1100 | 50 | Type: Surrette 6CS25P<br>Lifetime: 9645 kWh | 0-10 |
| Converter [42] | 300 | 300 | 0 | Lifetime: 20 years<br>Inverter efficiency: 95%<br>Rectifier efficiency: 95% | 0-6 |
| FC [45] | 3000 | 2500 | 0.02 | Lifetime: 40000 h<br>Min. load ratio: 25%<br>Efficiency: 50% | 0-8 |
| Electrolyzer [46] | 500 | 250 | 10 | Lifetime: 20 years<br>Min. load ratio: 0%<br>Efficiency: 85% | 0-8 |
| Hydrogen tank [42] | 574 | 574 | 10 | Lifetime: 25 years<br>Initial tank level: 20% | 0-6 |
| DG [46] | 200 | 200 | 0.5 | Lifetime: 15000 h<br>Max. efficiency: 31%<br>Min. load ratio: 30% | 0-5 |

Based on the input data, the software examines 460,800 different configurations using 1 to 4 equations and ranks them from lowest to highest NPC Total [47-49].

$$NPC = \frac{C_{ann.\ total}}{CRF\ (i.\ R_{proj})} \quad (1)$$

$$CRF = \frac{i\ (1+i)^N}{(1+i)^N - 1} \quad (2)$$

$$i = \frac{i' - f}{1 + f} \quad (3)$$

$$COE = \frac{C_{ann.\ total}}{E_{Load\ served}} \quad (4)$$

where NPC is net present cost ($), $C_{ann,total}$ is total annual cost ($), CRF is capacity recovery factor (-), i is annual interest rate (%), $R_{proj}$ is lifetime of project (year), N is useful life-time (year), i' is nominal interest rate (%), f is annual inflation rate (%), COE is cost of electricity ($/kWh), and $E_{load\ served}$ is real electrical load by system (kWh/year).

The amount of pollutants per liter of diesel used are 6.5 g of $CO_2$, 0.72 g of unburned hydrocarbons, 0.49 g of particulate matter, 2.2% of sulfur converted into particulate matter, and 58 g of $NO_x$.

## 5. Results

The results of the simulations are presented in Table 4. From the results of Table 4, it can be seen that the system based on wind energy (scenario 1) is superior to the system based on solar energy (scenario 2) in the studied area. Of course, it should be mentioned that scenario 2 is much more compatible with the environment because the percentage of renewable energy in scenario 2 is more than 2 times that of scenario 1.

Regarding the dispatch strategy, it should be mentioned that Cycle charging is economically superior to Load following, which shows that if the generator works at full capacity and the excess is stored in the battery, it is superior to the generator only providing the required amount of energy.

The lowest total NPC related to the first scenario is equal to 21544 $, which leads to the cheapest kWh of electricity produced with a value of 0.735 $ related to this scenario. Also, considering that wind energy can only supply 46% of the produced electricity, the generator should work for 4212 hours to supply the rest of the required electricity.

In the second scenario, which is based on solar energy, compared to the first scenario, costs have increased by about 2.3%, but the operating hours of the DG have decreased by about 90%. In the third scenario, which is the scenario of 100% use of renewable energy, compared to the first scenario, the cost of each kWh of electricity produced increases by 26%. In the fourth scenario, which is the traditional scenario based on fossil fuels, the cost of each kWh of electricity produced and the operating rate of the DG will increase by 27.6% and 42.7%, respectively, compared to the first scenario. In the fifth scenario, which is based on the FC, the FC generates 977 hours of electricity during the year, and only 1% of the electricity produced is generated by the DG. Compared to the superior economic scenario (scenario 1), the use of a FC causes a 36.6% increase in the cost of each kWh of electricity generated, but the number of hours of using a DG decreases by 91.7%. Figure 9 shows the average monthly electricity generation for the fifth scenario. According to Figure 9, from the total 12,400 kWh of electricity produced during the year, 69% of the electricity produced is provided by solar cells, 24% by wind turbines, 6% by FCs and 1% by DGs.

Based on the results of the simulations for the fifth scenario, there is 32.4% surplus electricity during the year, which can be sold to the neighbors to significantly reduce the system costs. The capacity factor of solar cells, wind turbines and f FCs are 19.6, 13.8 and 3.67 respectively. The performance contour of the FC during the year is given in Figure 10. It is clear from the contour that the performance of the FC is mainly at night when there is no sunlight. The maximum power output of the FC is between 1.62 kW and 1.8 kW. Another thing that can be seen from Figure 10 is that the FC performance is low in the months of February and March, which according to Figure 11, the reason for this is that hydrogen production in these months is the lowest during the year. Also, the reason that the production of hydrogen and consequently the performance of the FC is higher during the night hours is that the amount of electricity required during the night hours is less and the excess electricity for water electrolysis is more.

Figure 11 shows the monthly average hydrogen production contour in kg/day. According to Figure 11, the highest and lowest hydrogen production is in the months of January and February, respectively. In total, 50.7 kg of hydrogen is produced annually by the electrolyzer, which is used in the FC. The cost of each kg of hydrogen produced is $105.8, which is due to the high price of electrolyzers, FCs and hydrogen tanks in Iran.

The pollutants produced in scenario 5, which is due to the use of 1% of the DG, are listed in Table 5. From the results, it can be seen that $CO_2$ is the most produced pollutant with an amount of 178 kg/year.

Table 4. Simulation results

| Scenario no. | System components | Dispatch strategy | Total NPC | COE ($/kWh) | Ren. frac. (%) | Gen (hrs) | FC (hrs) |
|---|---|---|---|---|---|---|---|
| 1 | 1 WT+ 1 Gen+ 2 Bat +2 Conv. | CC | 21544 | 0.735 | 46 | 4212 | 0 |
| 2 | 5 PV+ 1 Gen+ 6 Bat +2 Conv. | LF | 22039 | 0.751 | 98 | 429 | 0 |
| 3 | 5 PV + 10 Bat +2 Conv. | CC | 27177 | 0.927 | 100 | 0 | 0 |
| 4 | 1 Gen+ 6 Bat +2 Conv. | CC | 27511 | 0.938 | 0 | 6009 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 5 | 5 PV + 1 WT+ 2 FC+ 1 Gen+ 2 Bat+ +2 Conv.+ 2 Elec. + 2 $H_2$ Tank | LF | 29453 | 1.004 | 99 | 349 | 977 |

WT: Wind turbine; Gen: Generator; Bat: Battery; Conv: Converter; FC: Fuel cell; CC: Cycle charging; LF: Load following; Elec: Electrolyzer; PV: Photovoltaic panel; Ren frac: Renewable fraction; hrs: hours

Table 5. Production pollutants of scenario 5

| Emission | Amount (kg/year) |
|---|---|
| $CO_2$ | 178 |
| CO | 0.44 |
| Unburned hydrocarbon | 0.05 |
| Particulate matter | 0.03 |
| $SO_2$ | 0.36 |
| $NO_X$ | 3.92 |

Figure 12 compares scenario 5 (based on FC) and the traditional scenario (only DG). It is clear from Figure 12 that the investment return time is 3.43 years and at the end of the 25-year useful life of the project, there will be a profit of $186,000.

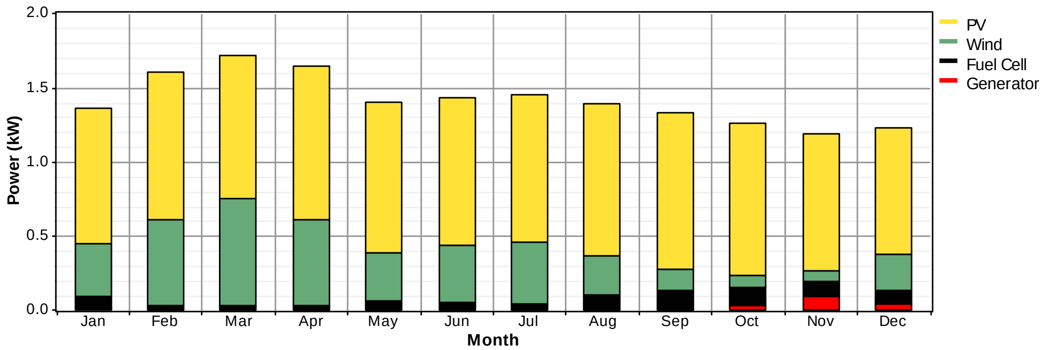


Figure 9. Monthly Average Electric Production

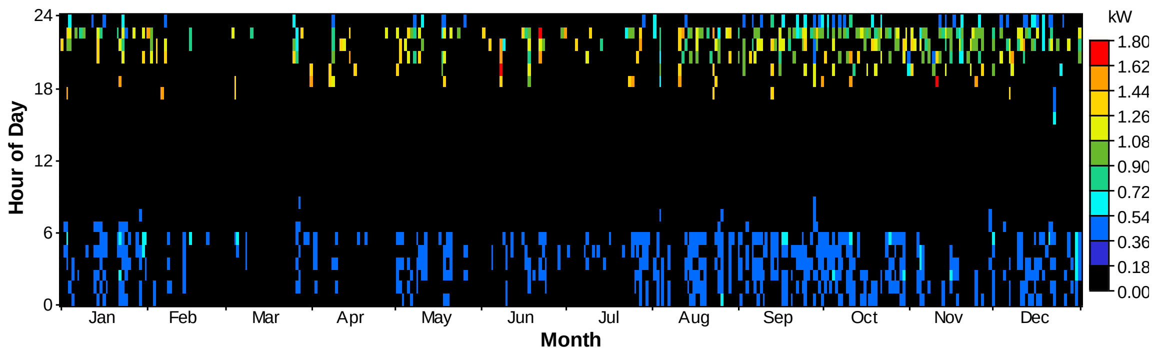


Figure 10. Fuel Cell Output

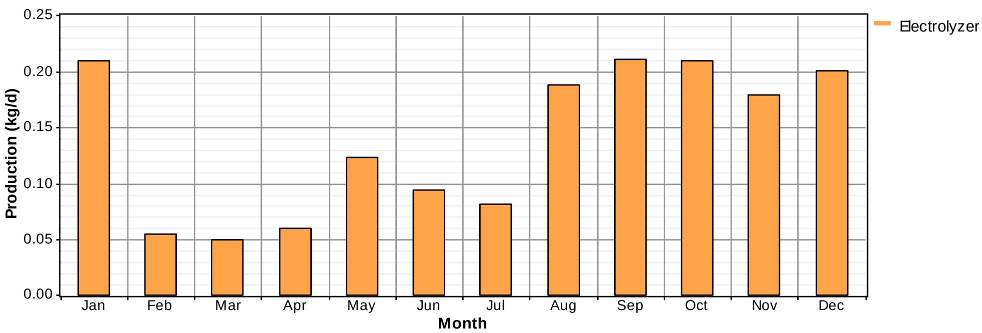


Figure 11. Monthly Average Hydrogen Production

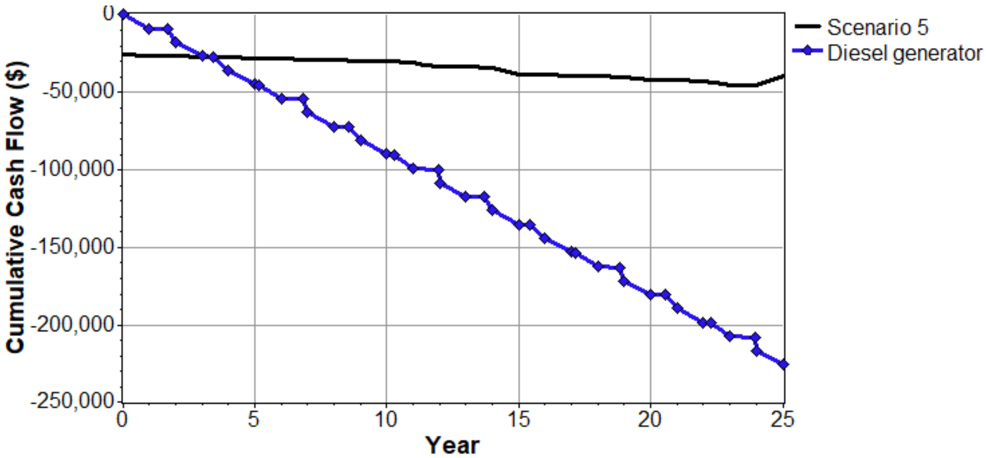


Figure 12. Current system (Scenario 5) compared to base case (only DG)

## 6. Conclusion

The production of electricity by FCs can be one of the sources of green energy production in a suitable replacement scale for traditional systems based on DGs, especially in rural and remote areas. Considering that this problem has either not been done in Iran or has been done in a certain region, in the present work, the potential of providing electricity for a rural residential house in Tamin village of Sistan and Baluchistan province using wind energy, solar energy and the FC is investigated. Technical-economical-environmental analyzes have been carried out during the 25 years of the useful life of the project and the selected systems have been compared with the system based on the DG (traditional system). The important results of the present work are:

- In the studied area, the use of wind energy is economically superior to the use of solar energy.
- In terms of environment, the system based on solar energy is superior to the system based on the wind turbine.
- The FC-based system produces and consumes 50.7 kg of hydrogen annually.
- In the FC-based system, the FC produces 6% of the total electricity produced.
- The payback time for the FC system is about 3.5 years compared to the traditional system (only DG).

## 7. Limitations of methodology and future works

Demand fluctuations over one hour are unreliable in HOMER. Moreover, voltage variability and current fluctuations cannot be applied from the source side, and the software can only take them into account in the overall output. Further, other potential complications, such as power cuts, transmission loss, and equipment failure, cannot be applied to the software. Regardless, HOMER still offers close-to-real results [50] and is widely used for analysis [51–55].

In the continuation of the present work, the system connected to the grid can also be checked, which was not done in the current work because the up-to-date operating and maintenance data for each km of the grid was not available. It is also possible to perform sensitivity analysis on climate data and equipment cost so that the results are generalizable for predictable variables, which was not done in the present work due to the need for high computer RAM. Finding the most suitable wind turbine as well as the storage battery is one of the other things that can be done in the future. Finding accurate and up-to-date information about these types of equipment as well as their availability in the Iranian market requires a comprehensive study that is time-consuming and therefore is not done in the present work. Also, by taking into account the pollution fines and finding the minimum distance from the national electricity grid in order to make the use of renewable energy cost-effective, it is possible to help decision-makers and investors in this field. Unfortunately, the exact price of each kilogram of pollutants produced in Iran was unavailable.

**Nomenclature**

| | |
|---|---|
| AC | Alternative current (-) |
| $C_{ann,total}$ | Total annual cost ($) |
| COE | Cost of electricity ($/kWh) |
| CRF | Capacity recovery factor (-) |

| | |
|---|---|
| DC | Direct current (-) |
| DG | Diesel generator (-) |
| $E_{load\ served}$ | Real electrical load by system (kWh/year) |
| f | Annual inflation rate (%) |
| FA | Firefly Algorithm (-) |
| FC | Fuel cell (-) |
| i | Annual interest rate (%) |
| i' | Nominal interest rate (%) |
| N | Useful life-time (year) |
| NPC | Net present cost ($) |
| PSO | particle swarm optimization (-) |
| PV | Photovoltaic (-) |
| $R_{proj}$ | Lifetime of project (year) |
| SATBA | Iran's Renewable Energy and Energy Efficiency Organization (-) |
| SFLA | Shuffled Frog Leaping Algorithm (-) |

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