ORIGINAL ARTICLE

Feasibility evaluation of an off-grid solar-biomass system for remote area electrification considering various economic factors

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Abstract
Off-grid renewable energy systems are a solution for power generation in areas where access to the grid is not possible or cost-effective; in particular, low population rural areas located far away from grid lines or in rugged terrains. Furthermore, over-reliance on fossil fuels for supplying global energy demand has led to the depletion of nonrenewable resources and environmental issues. This paper presents a feasibility assessment of an off-grid hybrid renewable energy system for a remote rural area in Kohgiluye and Boyer-Ahmad Province in Iran. Regarding the available energy resources in the region, a photovoltaic (PV)-biomass energy system is considered. HOMER Pro software is utilized to find the optimized sizing of the PV-biomass system to fulfill this load demand. The objective function in this optimization is the system’s total net present cost. Due to the rapid fluctuation of economic factors in the country, several rates of inflation and discount rate are considered to investigate their influence on the costs of the system. The optimization result for the current inflation rate of 40% and the discount rate of 18% in the country proposes a hybrid energy system consisting of a 3 kW biogas-fueled generator, 4.74 kW PV, 10 kWh battery, and 2.07 kW converter to meet the 2.64 kW peak load and 14.53 kWh/day consumption of the community. The total net present cost and cost of energy are $93,057 and 0.0933 $/kWh, respectively. Finally, the environmental assessment of the proposed hybrid system shows an annual CO$_2$ emission of 2.95 kg, which means 99.9% CO$_2$ emissions mitigation compared to a conventional coal-based electrical plant.

KEYWORDS
environmental analysis, HOMER, hybrid PV/biomass system, off-grid hybrid energy system, rural electrification, techno-economic
Affordable and clean energy is the 7th goal out of the 17 Sustainable Development Goals set by the United Nations. It aims to ensure affordable, reliable, sustainable, and modern energy for all. Although a crucial requirement for development in countries is access to energy, in particular electricity, it is reported by the Department of Economic and Social Affairs of the United Nations that 759 million people around the world lack access to electricity. Moreover, more than 85% of people live in rural areas, and electrification of rural areas is a vital necessity for remote places to reach economic growth, poverty reduction, employment, and promoting welfare. A big challenge for governments is to deliver electricity to small rural areas with a low population. Extending the power grid to these areas has many difficulties, including financial challenges such as the investment cost of grid facilities and transmission lines and procedural obstacles such as constrained transmission, rugged terrains, highly scattered valleys, and so forth.

On the other hand, the increase in global energy consumption and the decrease in fossil fuel resources and low-efficiency conventional energy systems have caused concerns about energy supply in the future. Besides, the current energy systems, especially in developing countries, which mainly use fossil fuels, raise environmental concerns. The resulting carbon emission leads to global warming, a severe environmental issue that, without proper management, threatens the environment, economy, and human life. Since economic growth is connected to the utilization of resources, particularly conventional nonrenewable resources, ensuring economic development along with a sustainable environment is challenging. These issues led to a drive toward alternative energy resources such as renewable energies, which can generate clean and sustainable energy without significant environmental impacts. The utilization of renewable energies can reduce CO$_2$ emissions and protect the environment. However, utilizing renewable energies in an off-grid system impose some constraints. Nevertheless, renewable energies are periodic and uncertain as they mainly depend on resources with stochastic nature. Moreover, system stability and balance between power production and demand are needed to guarantee the security of supply. For instance, energy generation in wind turbines and photovoltaic (PV) cells is intermittent depending on environmental factors. The utilization of storage or diesel generator alongside renewable energy systems could help the stability of electricity generation. Therefore a hybrid renewable energy system (HRES) is made by combining several renewable energy sources so that maximum efficiency is made by utilizing the benefits of these energy sources and covering their limitations. A hybrid energy system has higher reliability and efficiency than a single source-based system. Decentralized renewable energy systems are growingly employed as an alternative for grid extension and conventional fuels. To reach an affordable and efficient hybrid energy system, the sizing of the system should be in a way that minimizes the costs and maximizes the output power. HOMER software is one of the tools that conduct such an optimization.

Regarding the energy system of Iran, as shown in Figure 1, the source of electricity generation in the country is mainly natural gas, with 73% followed by oil and hydro with 15% and 9%, respectively. The other sources are coal, biofuel, wind, nuclear and solar PV, making up 3% of the electricity generation. So, the share of renewable energy in electricity generation in Iran is inadequate. As regards the emission, as illustrated in Figure 2, electricity generation in power plants accounts for the largest amount of CO$_2$ emission in the country among all sectors, that is, 29.1% of total CO$_2$ emission.

In terms of renewable energy resources, Iran is a rich country. The potential to utilize solar, wind, biomass, geothermal, biogas, and hydrogen power exist in Iran. For example, in the case of solar energy, Iran is placed in
the world’s Sun Belt, the direct normal irradiation (DNI) reaches up to 5.5 kWh/m²/day in the country, and there is an average of 300 sunny days per year. Regarding bioenergy, it is estimated that Iran has 63.7 TWh potential of energy from available biomass resources, of which 50 TWh corresponds to biogas, and the rest are bioethanol and biodiesel.

2 LITERATURE REVIEW

Many studies have been carried out so far regarding the utilization of hybrid renewable energy systems. Singh and Baredar performed a simulation and optimization of a solar PV, fuel cell, biomass gasifier, and battery energy system for an educational institute in India. Chambon et al. investigated biogas utilization in India’s off-grid and grid-connected rural areas and used HOMER to simulate a solar PV, biomass gasifier, diesel generator, and battery system. Shahzad et al. designed an economical and optimal hybrid system consisting of solar PV and biomass for a farm and its neighboring community in a small village in Pakistan using HOMER software. Suressh et al. studied a PV, biomass gasifier, diesel generator, and battery hybrid system for various load profiles and grid availability to electrify Jhawani village in India. Ali and Shahnia studied the economic and environmental viability of a hybrid energy system consisting of PV, wind turbine, diesel generator, and battery to be used instead of diesel generators for supplying the electricity of Laverton, one of Western Australia’s remote towns. Mandal et al. found an optimum hybrid energy system configuration consisting of PV, wind turbine, diesel generator, and battery to meet the electricity demand of a remote village in the northern region of Bangladesh. They investigated the economic, environmental, and social benefits of hybrid systems along with their challenges. In a study by Ghaem Sigarchian et al., a hybrid energy system composed of PV, wind turbine, battery, and biogas fueled generator whose fuel was produced locally by digestion of cattle manure, was simulated for a rural area in Garissa district in Kenya. Since using diesel generators is a common solution for power generation in remote areas, they examined the utilization of a diesel generator instead of the biogas generator in the hybrid system. Moreover, they compared this hybrid energy system with a system consisting of only a diesel generator and battery and performed an economic and environmental analysis. Muhammad et al. investigated the feasibility of off-grid solar PV systems for electrification of rural areas in the Punjab province of Pakistan. They found that electrification with solar PV is much cheaper than conventional means of electricity generation and that a significant amount of carbon emission mitigation can be achieved. Muhammad et al. used MATLAB and RETScreen to study the viability of employing solar PV in four big cities in India and found that solar energy is a proper energy choice because of available solar irradiations all over the year in those cities.

Several authors have investigated the utilization of hybrid renewable resources in Iran. Mehrpooya et al. investigated technical, economic, and environmental aspects of various combinations of diesel generators, PV, battery, and hydrogen systems (i.e., electrolyzer, H₂ storage, and fuel cell) to replace the diesel generators supplying electrical power of a laboratory at the University of Tehran in Iran. They also considered the impact of diesel fuel price variation on the cost of the hybrid energy system. In a study by Jahangir and Cheraghi, using HOMER, a hybrid energy system consisting of PV, biogas generator, wind turbine, and batteries were suggested as the optimum system for providing electricity to rural areas of Fars province, Iran. Moreover, the sensitivity analysis was also conducted at the input biomass rate, biomass price, and inflation rate. Rad et al. investigated the utilization of an off-grid or grid-connected hybrid renewable energy system consisting of PV, wind turbine, biogas generator, battery, fuel cell, and hydrogen tank to find an optimized system for electrification of a rural area northwest of Iran. They evaluated two common methods for hydrogen generation, that is, natural gas reformer and the electrolyzer. Mousavi et al. studied the viability of a hybrid renewable energy system for supplying electricity and drinkable water for remote villages in different climate zones of Iran. Then a comparison was made between the utilization of this hybrid system and grid extension. Ataei et al. used HOMER to investigate the technical and economic viability of a wind turbine, PV, and battery configuration for supplying electricity to a commercial building in Shiraz, Iran.

The main idea of this study is to design an off-grid hybrid renewable energy system to meet the load demands of a rural community in central areas of Iran. Since Kohgiluye and Boyer-Ahmad province is located in a mountainous area, the grid extension to its remote villages is quite tricky. Furthermore, since frequent blackouts happen in the country’s power grid, off-grid renewable energy systems can be a good solution for generating reliable and also clean electricity. The location of this province is shown in Figure 3. This region receives significant solar radiation suitable for power generation by PV cells. In addition, the efficiency of PV cells has been growing, and the manufacturing costs have been falling in recent years, that is, one-fifth
over the last decade, so the utilization of PV cells has become more economical. Besides, animal manure is abundant since livestock farming is common in the area. It could be a great source of biomass for producing biogas, so employing a biogas-fueled generator is reasonable as it can eliminate the cost of fuel and fuel transportation to the region compared to a diesel generator. So, regarding the available resources, a hybrid system consisting of PV, biogas-fueled generator, and battery is proposed. Therefore, the objective is to use HOMER software to optimize the sizing of the hybrid system components to reach the lowest cost and conduct a feasibility analysis. Furthermore, due to the country’s unstable economic conditions and especially the rapid variation of the inflation rate, the effect of economic factors fluctuations on the costs and performance of the system is analyzed. In the end, the emission of this hybrid energy system is compared with the emission of a coal-based power plant producing the same amount of electricity to analyze the environmental aspect of this hybrid system.

3 | METHODOLOGY

HOMER software developed by National Renewable Energy Laboratory (NREL) is used to design techno-economic optimum hybrid systems. This software is a powerful tool for determining the optimum sizing of components in off-grid and grid-connected energy systems. HOMER designs energy systems that can meet the electricity and thermal load using renewable and nonrenewable sources of energy. The economic analysis is performed regarding total net present cost (NPC) and cost of energy (COE). The total net present cost or NPC of a system is the current value of all costs, including the capital costs, replacement costs, O&M costs, fuel costs, emission penalties, and the cost of buying energy from the grid, minus the present value of incomes such as salvage value and revenue of selling power to the grid, during the project lifetime. Recommended configuration of the system in optimization results of HOMER are ranked based on the total NPC. The total NPC of the project is the sum of NPC of all system components and is calculated by summing the total discounted cash flows in each year during the project lifetime. Furthermore, total annualized cost and cost of energy are also calculated based on NPC. The total annualized cost is the annualized form of NPC and is needed for computing the cost of energy. The total annualized cost is expressed by the following equation:

\[ C_{\text{ann,tot}} = C_{\text{NPC}} \times CRF_{(i,N)}, \]

where \( C_{\text{NPC}} \) is the total NPC of the project and \( CRF_{(i,N)} \) is the capital recovery factor with the real discount rate of \( i \) and the project lifetime of \( N \). The real discount rate \( i \) and the capital recovery factor \( CRF_{(i,N)} \) are obtained by the following equations:

\[ i = \frac{i' - f}{1 + f}, \]

\[ CRF_{(i,N)} = \frac{i(1 + i)^N}{(1 + i)^N - 1}, \]

where \( i' \) is the nominal discount rate, and \( f \) is the annual inflation rate. Another critical economic criterion for economic analysis is the cost of energy or COE, the average cost per kWh of useful electrical energy produced by the system and shows cost-effectiveness. The COE is calculated by the following equation:

\[ C_{\text{COE}} = \frac{C_{\text{ann,tot}}}{E_{\text{served}}}, \]

where \( C_{\text{ann,tot}} \) is the total annualized cost and \( E_{\text{served}} \) is the total amount of energy that served the loads during the year.

In this study, after specifying the project’s location in HOMER software, an electric load assessment of the community is done to determine the load profile, peak load, and total daily consumption. Then the available energy sources for the PV-biomass system are evaluated. The solar radiation received in the area and the available biomass in the village is assessed. After that, components
of the system, including PV modules, biogas generator, battery, converter, and their data such as costs and lifetimes, are fed in HOMER. The simulation also considers two economic indicators of the country, that is, interest rate and inflation rate. Figure 4 indicates the methodology used for this analysis.

### 3.1 Load assessment

The desired system is to electrify a remote rural community. This community consists of six households, each of which uses a couple of electric appliances such as lighting, fan, TV, cell phone charger, and refrigerator. A water pump and a couple of street lights are also assumed as community loads. Load calculations, including appliances, numbers, nominal power, utilization hours, and total daily consumption, are shown in Table 1. The off-grid energy system should supply this daily energy demand and peak load.

Considering these appliances, the total daily consumption of a household is 2.77 kWh in hot months and 1.57 kWh in cold months, in addition to that a 3.3 kWh load as the community load is shared between all houses. Therefore, the total daily community consumption is 19.92 kWh in hot months and 12.72 kWh in cold months. Table 2 illustrate the utilization time of each appliance during a day.

There is no significant difference in the load profile of different months. That is because no electric cooling or heating devices exist in houses. In other words, no air conditioner and no electric heater are used in hot and cold months, respectively. The only difference is using a fan in hot months, that is, June to August. Hourly load distribution of the community during a day is shown in Figure 5. The peak load is 1.815 kW; however, some random variability is considered to make it more realistic, that is, a 10% day-to-day and a 10% timestep variability. Day-to-day variability applies some upward and downward change in the scale of the load profile on different days, and timestep variability adds some change in the shape of the load profile on different days. So after implementing this random variability, the peak load

![Diagram of methodology used for analysis.](image-url)

**Figure 4** Diagram of methodology used for analysis.

| Appliance          | Number | Power (W) | Utilization hours (h) | Consumption (kWh) |
|--------------------|--------|-----------|-----------------------|-------------------|
|                    |        |           | Cold months | Hot months | Cold months | Hot months |
| **Domestic load**  |        |           |             |             |             |             |
| Lights             | 4      | 15        | 7           | 7           | 0.42        | 0.42        |
| Fan                | 1      | 50        | 0           | 24          | 0           | 1.2         |
| TV                 | 1      | 80        | 4           | 4           | 0.32        | 0.32        |
| Cell phone charger | 1      | 10        | 3           | 3           | 0.03        | 0.03        |
| Refrigerator       | 1      | 100       | 9           | 9           | 0.8         | 0.8         |
| Total (one household) |    |           |             |             | 1.57        | 2.77        |
| **Community load** |        |           |             |             |             |             |
| Water pump         | 1      | 750       | 3           | 3           | 2.25        | 2.25        |
| Street light       | 5      | 15        | 14          | 14          | 1.05        | 1.05        |
| Total              |        |           |             |             | 12.72       | 19.92       |
reaches 2.64 kW. The daily load profile of each month is illustrated in Figure 6.

### 3.2 Available resources

This section evaluates available solar and biomass sources for the PV-biomass system considered for the region.

#### 3.2.1 Available solar irradiance

Based on data from the NASA database, the annual average solar global horizontal irradiance (GHI) in the region is 5.38 kWh/m²/day, and the maximum value is found to be 7.69 kWh/m²/day, a satisfactory amount for power generation in PV cells. The monthly profile of solar GHI and the clearness index in the region are demonstrated in Figure 7. The average monthly temperature needed for considering the temperature effect on PV modules’ power generation is presented in Figure 8.

HOMER uses Equation (5) to calculate the output of the PV array:

$$ P_{PV} = Y_{PV} \times f_{PV} \times \left( \frac{G_T}{G_{T,STC}} \right) \left[ 1 + \alpha_P (T_C - T_{C,STC}) \right], \quad (5) $$

where $Y_{PV}$ is the rated capacity of the PV array, that is, its power output under standard test conditions, $f_{PV}$ is the PV derating factor, $G_T$ is the current solar radiation incident on the PV array, $G_{T,STC}$ is the radiation incident at standard test condition, $\alpha_P$ is the temperature coefficient of power, $T_C$ is the PV cell temperature, and

### Table 2: Utilization time of appliances during a day

|                | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|----------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Light          |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Fan (hot months)|    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| TV             |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Cell phone charger |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Refrigerator   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Water pump     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Light          |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |

**FIGURE 5** Raw load profile of the community.
**FIGURE 6** Daily load profile.

**FIGURE 7** Average monthly solar GHI and clearness index. GHI, global horizontal irradiance.

**FIGURE 8** Average monthly temperature.
3.2.2 | Available biomass

Biomass is one of the oldest sources of energy that can be made from things such as agricultural residues, wood, animal, and human manure. The utilization of biomass as a source of energy has many benefits. For instance, agricultural and municipal waste can be used for energy generation instead of dumping in landfills, and since it can be replaced with traditional wood fuel, deforestation can be avoided. Furthermore, biogas production has a lesser carbon impact than fossil fuels, and a good fertilizer is also produced during this process.\(^{48}\) Biogas produced by the microorganism in the absence of oxygen can be used as the fuel for power generators. Depending on the source of biomass and the production process, the biogas composition can be different, but about 70% Methane (CH\(_4\)) and 30% Carbon Monoxide (CO\(_2\)) can be its simplified composition.\(^{42}\) The primary biogas sources in Iran are domestic and industrial waste, agricultural leftovers, animal dung, and 80% of garbage.\(^{49}\)

Livestock manure is a good source of biomass, and because of its availability in the project region is used as a part of the hybrid energy system. Available biomass in the region is given in Table 3. Considering six cows for each household means a total of 36 cows in this community. According to the following calculations, this number of livestock has the potential biomass production of 0.45 ton/day. Figure 9 shows the monthly average available biomass in the region. Equation (6) gives the total daily manure production.\(^{35}\)

\[
M = \sum_{n=1}^{i} N_i \cdot m_i,
\]

where \(M\) is the total manure production in tons/day, \(n\) in the number of groups of animals, \(N_i\) is the total number of animals and \(m_i\) is the manure production per head in tons/day.

3.3 | System design

This hybrid PV-biomass system consists of four main components, that is, PV modules, biogas-fueled generator, batteries, and converter. In this section, the characteristic of each component is explained. HOMER uses these components to find an optimum configuration to fulfill the electric load. Figure 10 shows the schematic of the hybrid energy system configuration.

For the solar section of the hybrid system, PV modules are utilized. The HOMER optimizer determines the capacity of the PV system. The technical specification of the PV module of this study is listed in Table 4.

3.4 | Biogas-fueled generator

Considering the region’s available livestock manure, HOMER will find the optimum capacity for the biogas-fueled generator. Since no fossil fuel is used, the fuel cost is zero. The generator’s costs and other technical parameters are provided in Table 5.

| Animal | Number \(N\) | Manure production per head \(m\) (kg/day) | Total manure \(M\) (kg/day) |
|--------|-------------|---------------------------------|-----------------|
| Cow    | 36          | 12.5                            | 450             |

\(T_{C,STC}\) is the PV cell temperature under standard test conditions (25°C).

FIGURE 9  Monthly average available biomass.

TABLE 3  Power generation potential of available biomass\(^{6}\)
Batteries

Batteries are utilized to store the power generated by solar panels during daylight for use in the absence of light. 12 V lead-acid batteries are used for this purpose. HOMER Optimizer determines the optimum quantities of the batteries. Table 6 provides the specifications of this storage system.

### Table 6: The storage costs and technical parameters

| Specifications                  | Values                                      |
|---------------------------------|---------------------------------------------|
| Capital cost                    | 223 $/kWh                                   |
| Replacement cost                | 203 $/kWh                                   |
| O&M cost                        | 105 $/year                                  |
| Lifetime (years)                | 5 years                                     |
| Lifetime (throughput)           | 800 kWh                                     |
| Nominal voltage                 | 12 V                                        |
| Nominal capacity                | 1 kWh                                       |

### 3.6 Converter

The power generated by solar modules is DC and converted to AC for electric appliances. A converter with a lifetime of 10 years and an efficiency of 95% is used, and HOMER Optimizer obtains the optimum capacity. The specifications of the converter are shown in Table 7.

### Table 7: The converter costs and technical parameters

| Specifications                  | Values                                      |
|---------------------------------|---------------------------------------------|
| Capital cost                    | 600 $/kWh                                   |
| Replacement cost                | 600 $/kWh                                   |
| O&M cost                        | 10 $/years                                  |
| Lifetime                        | 10 years                                    |
| Efficiency                      | 95%                                         |

### 3.7 Analysis

The lifetime of the project is considered to be 20 years. The economic indicators such as discount rate and the inflation rate are 18% and 40%, respectively. Now, regarding the available resources and constraints, a feasible and optimum hybrid system is simulated to fulfill the electric load of the region.

### 4 Results and Discussion

This section discusses the results of the HOMER software, that is, the optimum hybrid system. The objective function for this optimization is NPC. Each component's data, such as
categorized cost and the production of the solar and the biogas components, are given. Then a sensitivity analysis for investigating the effect of economic indicators variations on the NPC and COE of the system, plus an environmental analysis are performed. Finally, the simulation results are compared with other hybrid systems in similar studies to validate the results.

4.1 | Optimum system

As shown in Table 8, the optimum system consists of 4.74 kW PV modules, a 3 kW biogas-fueled generator, 10 kWh lead-acid batteries, and a 2.07 kW converter. The COE and NPC of this system are $0.0933 and $93,057, respectively. These values are acceptable for hybrid renewable energy systems costs. In the following sections, the COE of this system is compared with similar studies.

Table 9 provides the annual electricity generated by each part of the system, which consists of 23.8% of the biomass and 76.2% of the PV. Furthermore, 46.8% of the production, that is, 5138 kWh/year, is surplus electricity because the storage system is insufficient to store the energy generated by PV modules during the day. Increasing the storage capacity could reduce surplus electricity; however, this can bring the system out of the optimum point and increase the costs.

4.2 | Costs

Table 10 shows the detailed net present costs of system components. The costs include investment cost, replacement cost, O&M cost, fuel cost, and salvage revenue. The investment cost is $14,141, and it exists only in the project’s first year. Most of the initial capital cost is for PV modules. Regarding the replacement cost, if a component’s lifetime expires before the end of the project’s lifetime, that component needs to be replaced. The highest replacement cost belongs to batteries as they have the lowest lifetime among the system components, and as a result, every 5 years must be replaced. In the case of PV modules, since their lifetime is 20 years, the same as the project’s lifetime, no replacement is needed during this period, and as a result, its replacement cost is zero. Due to the high inflation rate in the country, it is better to use equipment with higher lifetimes to avoid frequent replacement of components. The O&M cost is calculated
yearly; however, it depends on operation hours in some components. Batteries have the highest O&M cost. The fuel cost is zero since the biomass is freely available in the region. The salvage cost is negative, which means it is revenue. The components can be sold at the end of the project's lifetime and make some income depending on their remaining lifetime. Equation (7) shows how the salvage value is calculated.

\[ S = C_{\text{rep}} \times \frac{R_{\text{rem}}}{R_{\text{comp}}}, \]

Where \( C_{\text{rep}} \) is the replacement cost, \( R_{\text{rem}} \) is the component's remaining life at the end of the project lifetime (years), and \( R_{\text{comp}} \) is the component lifetime (years). It can be seen that since the lifetimes of PV modules and the replaced converter end at the end of the project, the salvage value for these two components is zero. The salvage value exists only for the batteries and the biogas-fueled generator. The lifetime of the biogas-fueled generator is 20,000 h, and based on operation hours on this optimum result, it should be replaced after 12 years. So the remaining lifetime of the new generator at the end of the project lifetime is almost 4 years. In the case of batteries, as they need to be replaced every 5 years, they are replaced in the last year of the project, so at the end of the project, they are rather new, and the salvage value is high. By and large, the batteries are accounted for most of the costs. Regarding the costs type, the replacement costs have the highest expense.

### 4.3 Biogas fueled generator performance

Data of biogas-fueled generators are given in Table 11. 2614 kWh/year of electricity is produced by the generator, which means a capacity factor of 9.95%. Figure 11 illustrates power generation by biogas-fueled generator throughout the year. Most of the production is accounted for early nights when the load is high, and PV modules have no power generation. The generator production is also evident during the peak load of mornings. Furthermore, in hot months since the load is higher, it can be seen that the generator operation hours are more. At this optimum result, the generation of 2614 kWh/year for a 3 kW generator leads to a capacity factor of 9.95%. Lower operation hours of biogas-fueled generator means a higher remaining lifetime at the end of the project lifetime, so a high value of salvage can be gained in the current economic condition. Therefore, since the optimization is based on NPC, this low capacity factor for the generator is preferred.

#### Table 11 Summary of biogas fueled generator operation

| Parameter                  | Value | Unit     |
|----------------------------|-------|----------|
| Hours of operation         | 1672  | hours/year |
| Number of starts           | 687   | start/year |
| Operational life           | 12    | year     |
| Capacity factor            | 9.95  | %        |
| Fixed generation cost      | 0.255 | $/h      |
| Electrical production      | 2614  | kWh/year |
| Mean electrical output     | 1.56  | kW       |
| Minimum electrical output  | 1.50  | kW       |
| Maximum electrical output  | 2.64  | kW       |
| Fuel consumption           | 16.4  | tons/year |
| Specific fuel consumption  | 2.19  | kg/kWh   |
| Fuel energy input          | 8,753 | kWh/year |
| Mean electrical efficiency | 29.8  | %        |

#### Figure 11 Power output of biogas fueled generator.
4.4 | PV modules performance

Data of PV modules are given in Table 12. PV modules produce 8377 kWh/year of electricity, that is, a capacity factor of 20.2%. The power generation of PV modules throughout the year is shown in Figure 12. The production is limited to day hours in which sunlight is available, and at the hours of darkness, the power generation is zero. Therefore, when sunlight is available, PV modules supply the power, and the biogas-fueled generator act as a backup.

4.5 | Sensitivity analysis

To investigate how economic indicators such as discount rate and inflation rate affect the optimal system type, NPC, and COE of the hybrid system, a sensitivity analysis is conducted for the discount rate of 10% to 20% and the inflation rate of 10% to 40%. Figures 13 and 14 show the system’s NPC and COE based on the discount and inflation rates. It can be seen that the NPC goes up by increasing the inflation rate and lowering the discount rate. In the case of the COE, it goes up by lowering the inflation rate and increasing the discount rate.

Optimum results at different inflation rates and the current discount rate of 18% are shown in Table 13. It can be seen that a likely decrease in the inflation rate could change the optimum configuration of the system. A drop in the inflation rate reduces the optimum capacity of both the generator and PV modules. However, to meet the annual electricity demand of 5305 kWh, the operation hours of the generator increase, and as a result, the share of electricity production in the generator goes up, as shown in Figure 15. Once the share of electricity production in PV modules comes down, the excess electricity also decreases. Regarding the NPC, it decreases with lowering the inflation rate. On the other hand, the COE goes up at lower inflation rates as the total annualized cost becomes higher.

4.6 | Environmental analysis

The emissions of this hybrid renewable energy system are provided in Table 14. To investigate the environmental aspect of the system, a comparison of emissions from electricity generation in this system with a coal-based electrical plant is conducted. The CO2 emissions of a coal-based electrical plant are about 1.63 kg CO2/kWh, so the production of 10,990 kWh in these power plants leads to the emissions of 17,913.7 kg CO2 in a year; however, the CO2 emissions of the PV-biomass hybrid system is 2.95 kg. Therefore, up to 99.9%, of CO2 emissions mitigation can be achieved by utilizing this hybrid renewable energy system. Moreover, considering 10 $/tons CO2 as the international carbon price, $179,107 can be saved.

| Parameter          | Value | Unit    |
|--------------------|-------|---------|
| Rated capacity     | 4.74  | kW      |
| Mean output        | 0.956 | kW      |
| Mean output        | 22.9  | kWh/day |
| Capacity factor    | 20.2  | %       |
| Total production   | 8377  | kWh/year|
| Minimum output     | 0     | kW      |
| Maximum output     | 4.76  | kW      |
| Hours of operation | 4384  | hour/yr |
| Levelized cost     | 0.00958 | $/kWh  |

Abbreviation: PV, photovoltaic.

FIGURE 12 Power output of PV modules. PV, photovoltaic.
Comparison and evaluation

Table 15 provides the results of several similar studies in which hybrid energy systems are simulated with HOMER software. The COE of the current research is compared with these studies. At the country's current economic condition, the COE of the proposed hybrid system is $0.0933; however, any change in the value of economic factors can vary the COE of the system. It is evident from Table 15 that the value of the COE and those that can be obtained under other economic conditions are in the same range as similar studies.

### FIGURE 13
NPC of the system by inflation and discount rate. NPC, net present cost.

### FIGURE 14
COE of the system by inflation and discount rate. COE, cost of energy.

### TABLE 13
Optimum results for different inflation rates (current discount rate of 18%).

| Inflation rate (%) | PV (kW) | Biogas-fueled generator (kW) | Battery (kWh) | Converter (kW) | COE ($) | NPC ($) | System electricity production (kWh/yr) | System excess electricity (kWh/year) |
|--------------------|---------|------------------------------|---------------|----------------|---------|---------|----------------------------------------|-------------------------------------|
| 10                 | 0.74    | 1.00                         | 7.00          | 1.48           | 0.2271  | 12,490.84| 6025                                   | 414                                 |
| 15                 | 0.95    | 1.00                         | 7.00          | 1.41           | 0.1978  | 16,188.09| 6205                                   | 591                                 |
| 20                 | 1.29    | 1.00                         | 7.00          | 1.38           | 0.1723  | 21,913.06| 6568                                   | 949                                 |
| 25                 | 1.68    | 1.00                         | 7.00          | 1.36           | 0.1502  | 30,810.86| 7077                                   | 1458                                |
| 30                 | 1.74    | 1.00                         | 7.00          | 1.36           | 0.1315  | 44,880.47| 7174                                   | 1556                                |
| 35                 | 1.94    | 2.00                         | 5.00          | 1.13           | 0.1124  | 65,141.11| 7189                                   | 1578                                |
| 40                 | 4.74    | 3.00                         | 10.00         | 2.07           | 0.0933  | 93,056.57| 10990                                  | 5138                                |

Abbreviations: COE, cost of energy; NPC, net present cost; PV, photovoltaic.

### 4.7 Comparison and evaluation

Table 15 provides the results of several similar studies in which hybrid energy systems are simulated with HOMER software. The COE of the current research is compared with these studies. At the country's current economic condition, the COE of the proposed hybrid system is $0.0933; however, any change in the value of economic factors can vary the COE of the system. It is evident from Table 15 that the value of the COE and those that can be obtained under other economic conditions are in the same range as similar studies.
CONCLUSION

This study conducted a techno-economic-environmental analysis for an off-grid hybrid renewable energy system in remote rural areas in Kohgiluye and Boyer-Ahmad Province, Iran. A PV-biomass hybrid system was proposed to fulfill the electricity load regarding the available resources. The optimization results by HOMER software showed that a combination of a 3 kW biogas-fueled generator, 4.74 kW PV, 10 kWh battery storage, and 2.07 kW converter was the optimum configuration. The system’s economic analysis shows that the system’s NPC and COE were $93,057 and $0.0933, respectively. Due to the country’s unstable economic condition, a sensitivity analysis was performed to investigate the effects of the discount and inflation rate fluctuations on the system’s costs. The results showed a reasonable COE for the renewable hybrid energy system.

Furthermore, a likely decline in the inflation rate leads to a decrease in the NPC and an increase in the COE, but it will still be in an acceptable range. Nevertheless, establishing this hybrid energy system depends on many other factors, such as the country’s energy and economic policies. Additionally, the environmental analysis showed that this off-grid hybrid energy system could lead to 99.9\% mitigation of CO\(_2\) emissions.

Therefore, implementing such systems in rural areas instead of grid extension could significantly decrease the CO\(_2\) emissions of the country and also evade the blackouts that occasionally happen in the country’s...
power grid. More stringent environmental regulations in the country, such as carbon tax, the elimination of subsidy of power plants fuel, and the rise of global oil prices, would increase the cost of electricity production and reduce the net profitability. So policymakers can adopt supportive policies, such as tax concessions, subsidies, and bank loans, to ensure the reliability of the electricity supply in a rural area.

Finally, this study only considered a rural area in Kohgiluyeh and Boyer-Ahmad Province, Iran. Thus, the finding might be unsuitable for other regions with different energy consumption scales, load profiles, and available resources. Furthermore, other sources of energy such as wind or hydro can be considered in future research.

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