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Use of a Hybrid Wind–Solar–Diesel–Battery Energy System to Power Buildings in Remote Areas: A Case Study

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Abstract: The emerging environmental consequences of overdependence on fossil fuels have pushed many countries to invest in clean and renewable sources of power. Countries like Iran where these sources can be found in abundance can take advantage of this potential to reduce their dependence on fossil fuels. This study investigated the feasibility of the standalone use of a hybrid renewable energy system (HRES) to power buildings in the Bostegan village in the Hormozgan province of Iran. Technical, economic, and environmental assessments were performed with the help of the Hybrid Optimization of Multiple Energy Resources (HOMER) software, and the optimal configuration for the system components was determined accordingly. The results showed that the simultaneous use of wind and solar systems with a converter and a backup system comprised of a diesel generator and batteries will be the most economic option, offering electricity at a cost of 1.058 USD/kWh and with a renewable fraction of 64%. After selecting the most optimal system using the step-wise weight assessment ratio analysis (SWARA) and weighted aggregated sum product assessment (WASPAS) techniques, a sensitivity analysis with 27 parameter settings was performed to determine the effect of fuel price fluctuations and the uncertainty in the renewable energy potentials on the results. This analysis showed that in the worst-case scenario, the price of electricity will reach as high as 1.343 $/kWh. In the end, the study investigated an alternative scenario where the generated power is used for hydrogen production, which showed that the system output can be used to produce 643.63 ton-H2/year.

Keywords: hybrid renewable energy system; sensitivity analysis; HOMER software; rural electrification; hydrogen production; multi-criteria decision-making methods

1. Introduction

Today, access to electricity can be viewed as a measure of the sustainable economic development of a nation and the prosperity of its citizens. Indeed, no country can grow and prosper without securing access to energy sources such as electricity [1]. In recent decades, the combination of fast population growth and rapid technological development has created a huge demand for energy, especially electric power. Meanwhile, many rural and remote areas, especially in developing countries, still lack access to electricity. This problem can be solved by either expanding power grids or building off-grid power generation systems. While a large portion (roughly 75%) of the world's electricity still comes from fossil fuel sources [2], the problems associated with overreliance on these fuels, including environmental degradation and climate change due to CO_2 emissions [3], have turned renewable energy sources such as wind [4,5], solar [6], and geothermal [7,8] into viable alternative sources of energy. However, there are still many problems with the use of standalone off-grid renewable systems to meet localized power demand, most notably high investment costs and low reliability due to the inherent uncertainty of renewable energy sources [9]. The concept of a hybrid renewable energy system (HRES) has been developed to tackle this challenge [10]. HRES is a system of conventional and renewable energy sources that is designed to generate and store electricity for a localized demand point in a standalone or off-grid state. HRES can be used to bring electricity to remote and rural areas that are hard to reach through conventional means. Given the uncertain nature of renewable sources, these systems use a range of conventional energy sources (fossil fuels) and energy storage devices (e.g., batteries) as backup sources to ensure high reliability. As a result, HRES is more reliable than standalone renewable energy systems. It is also possible to build on-grid varieties of HRES for places such as universities, hospitals, factories, and even cities [10]. However, the main feature of HRES is its ability to bring electricity to remote and rural areas through the use of renewable sources, which leads to reduced greenhouse gas emission and potentially reduced levelized cost of energy (LCOE). These benefits are in line with the objectives of sustainable development in its economic, environmental, and social dimensions.

Another energy source that is expected to play a bold role in the replacement of fossil fuels is hydrogen. Indeed, there is a wide range of benefits in using hydrogen as fuel. For example, each kilogram of hydrogen can produce about 39.4 kWh of power during combustion, which is three times more than other fuels (liquid hydrocarbons). Additionally, this fuel releases water during combustion and can easily replace fossil fuels in many processes and engines [11]. Therefore, there are great benefits to including hydrogen production units in HRES.

One of the important issues in designing an HRES is how to optimize its components (e.g., the specifications of wind turbines, photovoltaic panels, batteries, generators, and converters) so that it can optimally achieve its objectives. Many software applications and optimization methods have been developed for this purpose. One of the most powerful tools for determining the optimal number and specifications of equipment in an HRES is the software called HOMER (hybrid optimization of multiple energy resources), which has been developed by the United States National Energy Renewable Laboratory (NREL) [12]. In this study, this software was used to reach the first research goal, that is, to determine the optimal composition of an HRES for a remote village in the south of Iran (Bostegan, Hormozgan province). Bostegan is a rural relative of the functions of the Bashagard section of Jask city in Hormozgan province. In this village, to provide the required energy, they use burning wood and fossil fuels. Most of the residents of this village are farmers and ranchers. The access of buildings and residents of this village to electricity is at a very low level, and there are many problems regarding energy supply in this area. Therefore, the generation of sustainable electricity from renewable sources is very important considering the potentials of the southern regions of Iran in the field of renewable energy such as wind and solar energy.

The cost of bringing electricity to remote rural communities with very low consumption could be surprisingly high. In many cases, the low demand makes it uneconomic and impractical to build and maintain grid lines in these areas [2]. While it might be a good idea to give diesel generators to these communities, the cost of fuel and the cost of transporting it from other areas could also be significant. Furthermore, there could be as much uncertainty in these costs as there are in renewable energy sources. Thus, another objective of this study is to investigate these uncertainties by conducting a sensitivity analysis on diesel prices and potential fluctuations in wind and solar output. In this study, analyses were carried out based on two scenarios. In the first scenario, the optimal composition of HRES was determined with the assumption that the government will build the proposed system to power the village. However, since the village might still become uninhabited because of the lack of other resources, in the second scenario, it was assumed that the government will make the investment with the purpose of converting the generated electricity into hydrogen and transferring it to oil refineries in the south of Iran.

Hydrogen is widely used in the production of petroleum and petrochemical products and plays an important role in the development of oil-related industries and the Iranian economy [13]. Hydrogen production systems from renewable energy have been the subject of various studies [14]. Hydrogen production from renewable energy has been performed in different regions of Iran, such as Baluchestan [15], the Southern and Northern coasts of Iran [16], Firuzkuh [17], Fars Province [18], etc. Meanwhile, the production of hydrogen from renewable energy in Bostegan has not been studied so far. According to the research literature, Bostegan has good potential in terms of renewable energy. At present, hydrogen energy as a sustainable energy source is superior to other energy sources in terms of technological efficiency and economic and environmental issues. The most important advantages of hydrogen energy sources over other energy sources include: (1) burning hydrogen gas produces a lot of heat and (2) it does not produce pollutants (e.g., CO_2, SO_2, and NO_2) [19]. About 96% of the hydrogen produced in world markets is supplied through traditional methods such as fossil fuels. This energy supply consists of three areas: 50% through natural gas reforming, 30% through oil refineries, and 18% through coal [20]. For each ton of hydrogen produced by the above methods, 2.5–5 tons of CO_2 emissions are produced [21]. The remaining 4% of hydrogen is obtained by the electrolysis of water. This method has led to socio-economic stability when the necessary power for the electrolyzer is generated through renewable energies [22]. Hydrogen production as a positive advantage for investors and the government for electricity supply in case of the depopulation of the village, as an alternative scenario to reduce investment risk, is proposed in this study.

Therefore, this study is a technical, economic, and environmental evaluation of the use of HRES to power a rural area in southern Iran. The objectives and innovations of this study are as follows: (1) this is the first study on the use of HRES to power remote areas without grid access in Iran; (2) this is the first study to optimize the components of HRES for this purpose; (3) the results can be used for neighboring villages and other underdeveloped areas with similar climate (e.g., in Afghanistan); (4) a sensitivity analysis with 27 parameter settings has been performed on the parameters that might influence the price of generated electricity; (5) this is the first study to investigate hydrogen production from HRES built-in remote areas as a risk reduction solution. Regarding the last item, it should be explained that the government tends to not take the risk of investing in renewable energy in remote rural areas that could become uninhabited in the future, but by bringing hydrogen production into the picture, the present study offers a way to hedge this risk and raise the confidence in the viability of this investment.

2. Review of Literature

Many studies have highlighted the existence of great potentials for harvesting renewable energies in Iran. In a study by Alamdari et al. [23], where they investigated the solar power potential of 63 locations in Iran, the greatest potentials were observed in the southeastern parts of Khuzestan province. A study by Firouzjah [24] on the economics of using photovoltaic panels in several Iranian provinces also reported that there are good potentials for using solar energy in Iran. In another study by Alamdari et al. [25] on the wind energy potential in 68 locations throughout Iran, it was reported that wind power in the eastern and northeastern parts of Iran is more suitable for large applications, but in other parts, it is better to use smaller wind turbines. Saeidi et al. [26] evaluated the wind energy available at heights of 10, 30, and 40 m in the North Khorasan and South Khorasan provinces of Iran. In a study by Mostafaeipour et al. [27], they investigated the potential for generating electricity from wind energy in Binalood, Iran. This study, which was conducted by the use of wind speed data collected in a station in Binalood, showed that there is significant wind energy potential in this area. Nematollahi et al. [28] evaluated the techno-economic viability of hydrogen production from renewable solar–wind energy sources in Sistan and Baluchestan provinces in southern Iran. These researchers reported that the province has great potential for wind and solar power generation. In another study by Mostafaeipour et al. [29], they investigated the potential for hydrogen production from wind energy sources in the Ardabil province of Iran for industrial and agricultural purposes. Similar studies have been conducted on the wind energy potential in other parts of Iran including Semnan [30], Yazd [31], Kerman [32], and Fars [33].

Over the years, a number of studies have examined the use of HRES to power buildings in remote areas that lack grid access in Iran and other parts of the world. For example, Adaramola et al. [34] conducted an economic assessment on the use of an HRES consisting of PV panels, wind turbines, and diesel generators for remote areas in southern Ghana. This study reported that the HRES with the optimal configuration, which will consist of PV panels with a capacity of 80 kW, a wind turbine with a capacity of 100 kW, a diesel generator with a capacity of 100 kW, a converter with a capacity of 60 kW, and 60 units of battery, will be able to provide electricity at a price of 0.281 $/kWh. In a techno-economic assessment of photovoltaic solar power generation on a remote island (Andaman and Nicobar Islands) in India, Bhakta et al. [35] reported that the optimal configuration would consist of solar panels with a capacity of 2.5 kW, 12 batteries, and a converter with a capacity of 2.0 kW. It was also reported that the cost of electricity to be generated would be 0.398 $/kWh. Olatomiwa et al. [36] conducted a techno-economic assessment of power generation with solar, wind, and diesel sources in a number of villages in six regions of Nigeria. This study reported that for all six regions, the PV/diesel/battery PV/diesel HRES had the lowest NPC among the assessed configurations. Rehman and Al-Hadhrami [37] assessed the performance of a PV/diesel HRES with backup batteries for a village in Saudi Arabia. These researchers reported that the proposed HRES will be more feasible if there is an increase in fuel prices. A study conducted in Palestine showed that for remote areas, it is more cost-effective to use PV-diesel HRES than to use standalone diesel generators [38]. In a study by Jahangiri et al. [39], the Homer software was used to assess the feasibility of building off-grid solar power systems in rural areas of Chaharmahal Bakhtiari province in Iran. The results of this study showed the best configuration to be 2 kW solar panels, a 1 kW diesel generator, and a 1 kW converter. The minimum cost of electricity generation in this area was estimated to 0.79–1.35 $/kWh. Mostafaeipour et al. [40] used the Homer software to assess the techno-economic feasibility of wind power generation in the Gachsaran region of Iran. This study reported that the optimal system, which consists of a 10 kW wind turbine, a 12 kW converter, a 12 kW diesel generator, and eight batteries, will have annual revenue of 8538 $/year. In a techno-economic assessment of an HRES for the remote areas of Bangladesh, Das et al. [41] used the HOMER software to optimize the components of solar panels, wind turbines, batteries, biogas units, and diesel generators for meeting the electricity demand. Al-Sharafi et al. [42] performed an economic study on the use of solar–wind systems for hydrogen production in Saudi Arabia and then optimized a system designed for this purpose.

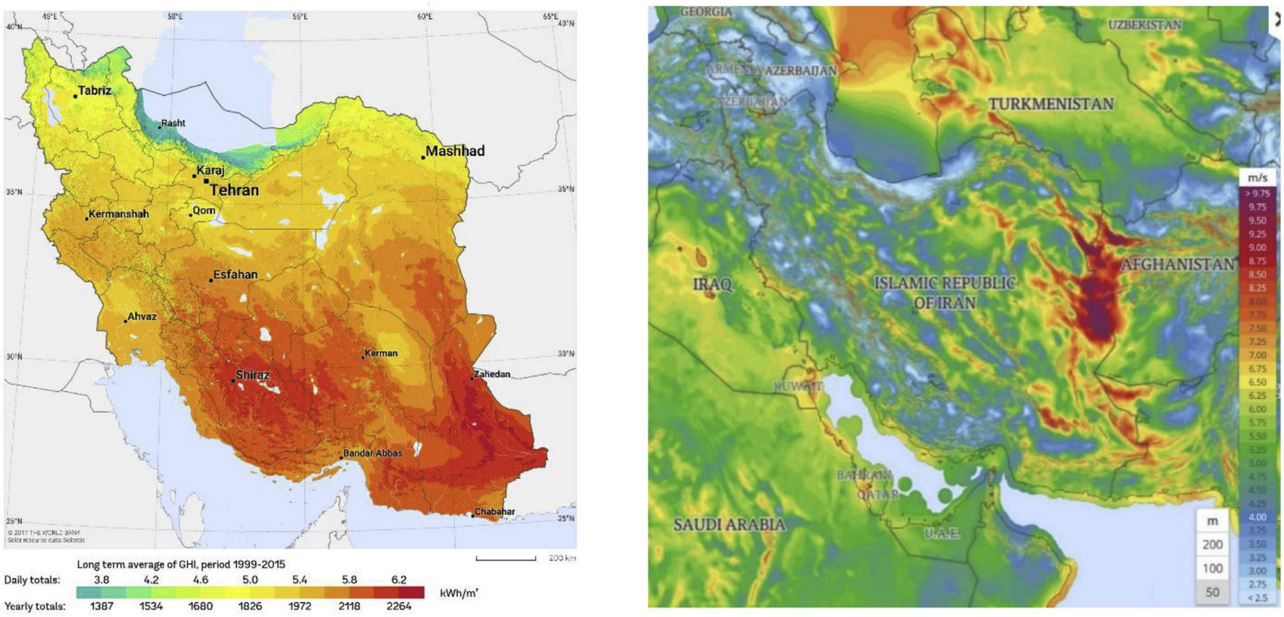
The review of the literature shows that so far, there has been no study on the use of HRES and optimization of its components for powering remote areas in southern Iran. Bostegan is a rural relative of the functions of the Bashagard section of Jask city in Hormozgan province. In this village, to provide the required energy, they use burning wood and fossil fuels. Most of the residents of this village are farmers and ranchers. The access of buildings and residents of this village to electricity is at a very low level, and there are many problems regarding energy supply in this area. Therefore, the generation of sustainable electricity from renewable sources is very important considering the potentials of the southern regions of Iran in the field of renewable energy such as wind and solar energy.

Additionally, this study is the first to perform a comprehensive sensitivity analysis with 27 parameter settings to examine the effect of parameters that might affect the price of generated electricity. Another innovation of this study is the introduction of an alternative scenario for reducing the risk of investment in remote areas, which involves using the generated electricity to produce hydrogen and directing the produced hydrogen to oil refineries in southern Iran.

3. Materials and Methods

3.1. Study Area

This study investigated the viability of a wind–solar–diesel hybrid energy system with batteries for powering the buildings of a remote village called Bostegan under different scenarios. This village is located at 26°27′ N latitudes and 57°53′ E longitudes in Hormozgan province in the southeast of Iran. The southern regions of Iran are known to have good renewable energy potentials. As shown in Figure 1, the study area is one of the most suitable areas in the region for harvesting both wind and solar power.



(**a**) (**b**)

Figure 1. Potential of renewable energy sources in Iran: (**a**) solar irradiation received on a horizontal surface, (**b**) wind speed at a height of 50 m [28].

It can be seen that the southern regions of the country have a good potential for harvesting renewable energies. The village of interest has a school, and roughly one-quarter of its inhabitants are literate. The inhabitants' main energy sources for cooking and heating are firewood and small amounts of diesel. The houses and the school of this village do not have access to electricity. Naturally, access to electricity is the top priority for the development and improvement of education and comfort situation in such villages.

3.2. Estimation of Electricity Consumption

Since the village has never had an electricity supply system and therefore no system for measuring consumption, it was necessary to estimate the amount of electricity to be consumed in the village. According to previous studies [2], the amount of electricity consumed in a village can be determined based on the number of households, the power-consuming devices and appliances used by each household, and the consumption of service providers. Using this approach, the electricity consumption of the village was estimated for 20 households. The estimated electricity consumption model for households and service centers, which is based on previous studies in Iran [43–45], is shown in Figure 2. According to this model, the average electricity consumption of households and service centers is 5.625 and 22.35 kWh/day, respectively. To make sure that the system can handle load fluctuations, these figures were assumed to be subject to 10% random hourly changes and 15% random day-to-day changes. The estimated monthly load over a period of one year is shown in Figure 2. These estimates were used as one of the main inputs of the HOMER software.

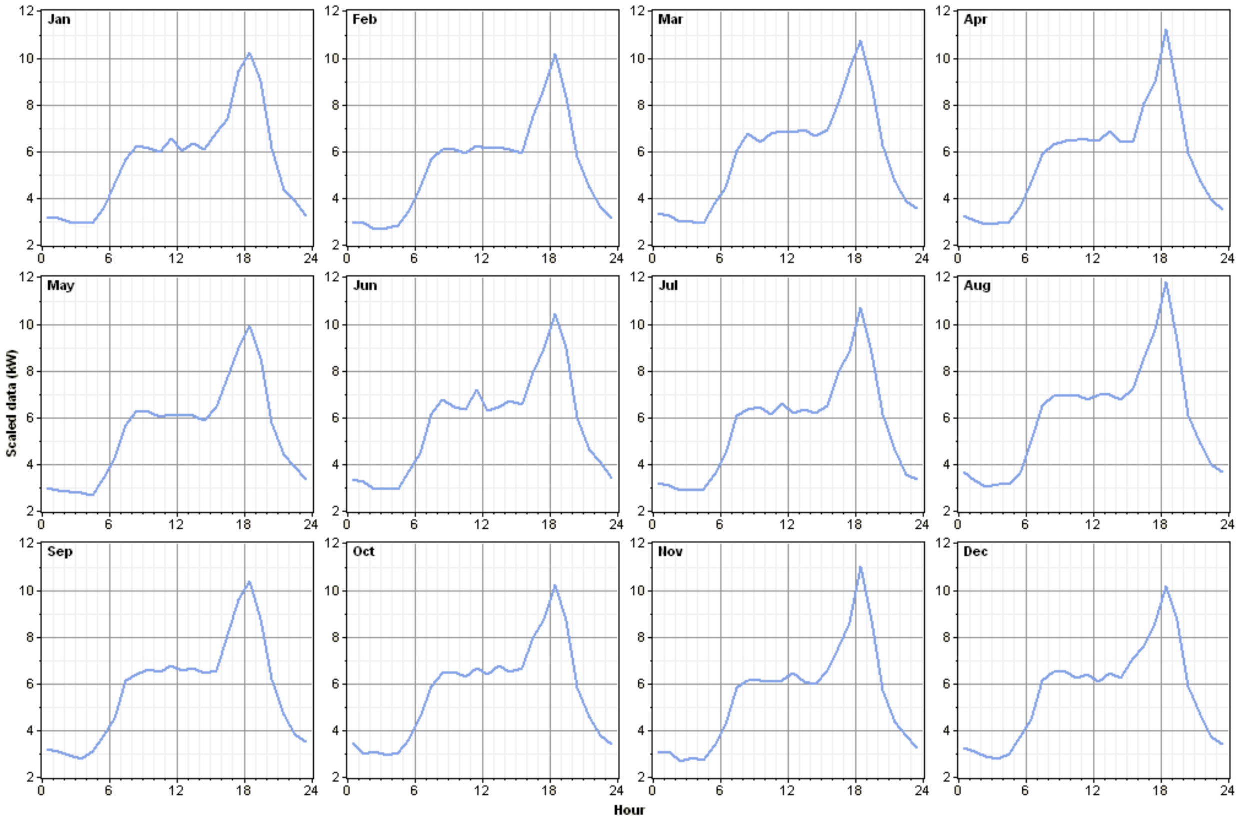


Figure 2. Distribution of estimated electricity load in the study area over a period of one year.

3.3. Specifications of the Considered Hybrid Energy System

The hybrid system was considered to be consisting of a wind turbine, photovoltaic panels, a diesel generator, and batteries. It was assumed that batteries store the excess electricity generated by renewable energy sources and that battery power will be used only when there is not enough renewable energy to meet the demand. The diesel generator was considered as a backup power source that is switched on when batteries and renewable energy sources do not provide enough power to meet the demand. The schematic diagram of the considered hybrid system is illustrated in Figure 3. The first research objective was to determine the best configuration and capacity for the components of the renewable energy system based on NPC and LCOE.

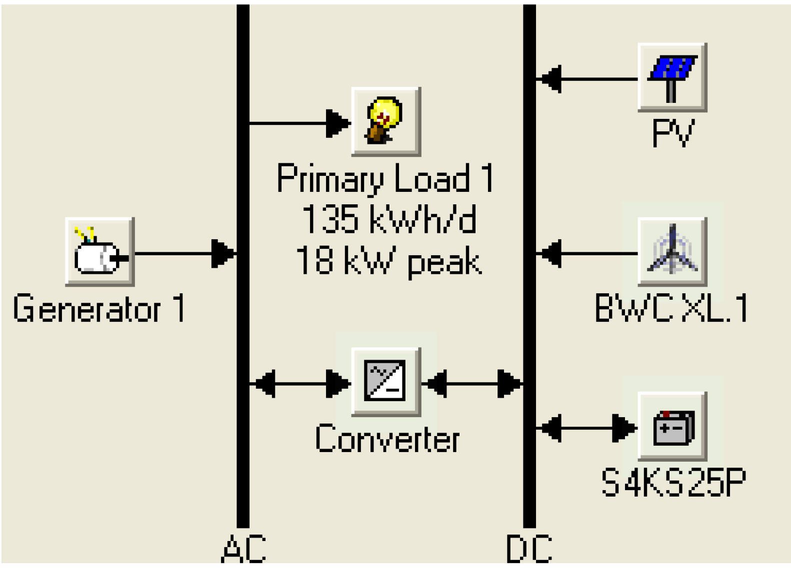


Figure 3. Schematic diagram of the proposed hybrid system.

3.4. Solar Panel

Modeling and implementation of solar power systems in a region involve three factors: the amount of solar radiation in that region, the cloudiness (or clearness) index of that region, and the area required for the construction of the power plant [2]. The amount of solar radiation received in a region can be easily estimated based on its geographical location. The difference between solar radiation at the top and bottom of the atmosphere with cloudiness taken into account can be expressed as follows [46]:

$$\overline{\mathrm{K_T}} = \frac{\overline{\mathrm{H}}}{\overline{\mathrm{H_0}}} \tag{1}$$

where $\overline{\mathrm{H}}$ is the monthly average GHR, $\overline{\mathrm{H_0}}$ is the radiation that is received in the same place without taking the atmosphere into account, and $\overline{\mathrm{H_0}}$s obtained by Equation (2):

$$G_{on} = G_{sc}\left[\,1 + 0.033\ Cos\left(\frac{360n}{365}\right)\right] Cos\ \theta_z \tag{2}$$

In this equation, G_{sc} called the solar constant is equal to 1364 $\mathrm{W/m^2}$. The parameter n represents the number of days since the first day of January (for 1 January, n = 1). The angle between the solar rays and the vertical line, which is called the zenith angle, can be obtained as follows:

$$Cos\ \theta_z = Cos(\delta)Cos(\phi)Cos(\omega) + Sin(\delta)Sin(\phi) \tag{3}$$

By setting $\theta_z = 90$, the angle of sunrise and sunset can be determined as follows:

$$\omega_s = Cos^{-1}(\tan\phi \tan\delta) \tag{4}$$

With the integration of Equation (2) from sunrise to sunset, the equation of (5) determines the amount of daily radiation:

$$H_0 = \frac{24}{\pi}\ G_{sc}\left[1 + 0.033Cos\left(\frac{360n}{365}\right)\right] \times \left[Cos\phi\ Cos\delta\ Sin\omega_s + \frac{2\pi\omega_s}{360}\ Sin\phi Sin\delta\right] \tag{5}$$

Here, H_0 is in Wh/m^2 day. The monthly average H_0 for each month must be calculated based on the average n of that month. The amount of solar radiation in the study area was obtained from the NASA database based on latitude and longitude [47].

In this study, it was assumed that solar power will be harvested by photovoltaic panels. Since these panels only work during daylight hours, the excess electricity needs to be stored in batteries, which act as a backup source when required. In a renewable system consisting exclusively of solar panels, batteries are the only support component. In a solar–wind system, wind energy will be the source of power during non-sunny hours. In a solar–wind–battery system, batteries act as a backup source when renewable energies cannot meet the demand. In a solar–wind–battery–diesel system, batteries and diesel generators both act as backup sources. The amount of electricity generated by a photovoltaic system can be calculated as follows [48]:

$$P_{pv} = Y_{pv} f_{pv} \left(\frac{\overline{G_T}}{\overline{G_{T,STC}}} \right) \left[1 + \alpha_p (T_c - T_{c,STC}) \right] \tag{6}$$

where Y_{pv} is the electricity output of solar cells under standard conditions in kW, $\overline{G_T}$, is the incident solar radiation on the cell surface in kW/m^2, $\overline{G_{T,STC}}$ is the incident solar radiation on the cell surface under standard conditions, which is 1 kW/m^2, T_c is the cell temperature at each time step, $T_{c,STC}$ is the cell temperature under standard conditions, and f_{pv} is the derating factor. The specifications considered for solar panels are given in Table 1. To optimize the panel capacity, this parameter was changed from 0 to 100 kW in steps of 10 kW.

3.5. Wind Turbine

The second renewable source of the considered system is wind energy. The amount of electricity generated by wind turbines strongly depends on the wind speed and consistency and characteristics of the wind turbine. The power output of a wind turbine generator can be expressed as [49]:

$$P(v) = \frac{1}{2} C_p A \rho v^3 \tag{7}$$

where C_p is the power coefficient of the turbine (i.e., electricity produced by the wind turbine/total energy available in the wind), A is the swept rotor area of the turbine, and r is the air density. In the rated region, the power remains constant and is defined as the rated power P_r. The turbine is shut down when the wind speed exceeds v_f to prevent damage. The power curve can be written as [49]:

$$P(v) = P_r \begin{cases} 0 & v < v_c \\ P_n(v) & v_C \le v < v_r \\ 1 & v_r \le v \le v_f \\ 0 & v > v_f \end{cases} \tag{8}$$

The power curve for wind turbines is shown in Figure 4.

In this study, wind speeds at the height of 10 m in the study area were obtained from the NASA database [47]. The specifications of the considered wind turbine are given in Table 1. To optimize the turbine capacity, this parameter was changed from 0 to 100 kW in 10 kW steps.

3.6. Converter

The efficiency of a converter indicates how much of a given DC power it converts to AC power. Conversely, the efficiency of a rectifier is the AC-to-DC power conversion ratio. A generic converter is considered for this study with an efficiency of 95% and 100% rectifier relative capacity. The techno-economic specifications of the converter are given in

Table 1. To optimize the converter capacity, this parameter was changed from 0 to 150 kW in 10 kW steps.

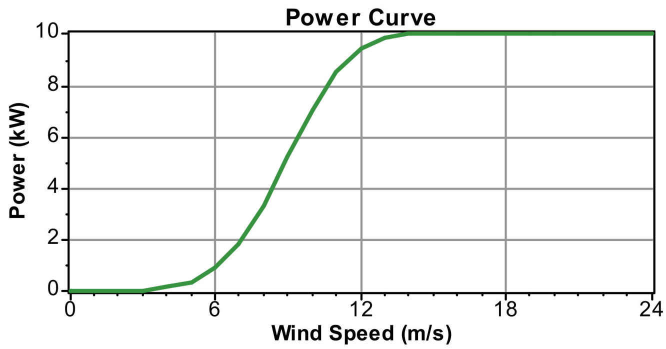


Figure 4. Power curve intended for wind turbines.

3.7. Diesel Generator

It was assumed that a diesel generator is used as a backup source to produce extra power when the electricity output of renewable sources is not enough to meet the demand. The majority of calculations in this part of the study are related to the fuel curve. The fuel curve indicates the amount of fuel that the generator uses to generate electricity. For simplicity's sake, the fuel curve was assumed to be a straight line. Therefore, the fuel consumed by the generator was formulated as follows:

$$\dot{m}_{fuel} = F_0 Y_{gen} + F_1 P_{gen} \tag{9}$$

where F_0 is the interpolated coefficient of the fuel curve (Figure 5), F_l is the slope of the fuel curve (Figure 5), Ygen is the nominal power of the generator, and Pgen is its power output. The efficiency of the generator can be defined as the amount of electrical energy that leaves the system relative to the amount of energy consumed during the combustion process:

$$\eta_{gen} = \frac{3.6\ P_{gen}}{\dot{m}_{fuel} LHV_{fuel}} \tag{10}$$

In this equation, LHV_{fuel} fuel is the lower heating value of the fuel. The fuel curve of the diesel generator is displayed in Figure 5 and its specifications are given in Table 1. To optimize the capacity of the diesel generator, this parameter was changed from 0 to 100 kW in 10 kW steps.

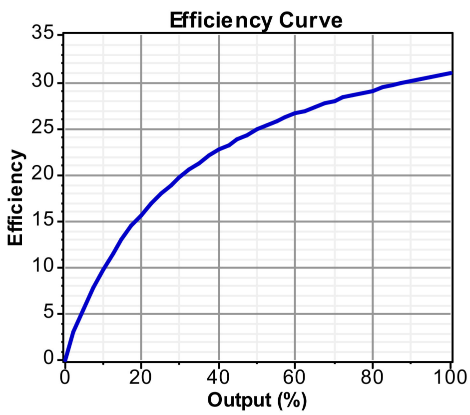


Figure 5. Efficiency curve of the diesel generator.

3.8. Battery

When the electricity generated by renewable energy systems exceeds the demand, the excess electricity needs to be stored in batteries. This stored electricity can be used later when renewable sources do not produce enough power to meet the demand. When renewable energy systems and batteries cannot meet the demand, the diesel generator must be turned on to act as a backup power source. There are certain limitations in the charge and discharge of batteries, which can be formulated as follows:

$$P_{batt,cmax,kbm} = \frac{kQ_1 e^{-k\Delta t} + Qkc\left(1 - e^{-k\Delta t}\right)}{1 - e^{-k\Delta t} + c\left(k\Delta t - 1 + e^{-k\Delta t}\right)} \tag{11}$$

where Q_1 is the energy available in the battery at the beginning of the time step in kWh, Q is the total energy in the battery at the beginning of the time step in kWh, c is the battery capacity ratio, k is the battery rate constant in 1/h, and Δt is the length of the time step h. There is another limitation regarding the maximum charge of the battery, which can be expressed as follows:

$$P_{batt,cmax,mcr} = \frac{\left(1 - e^{-\alpha_c \Delta t}\right)(Q_{max} - Q)}{\Delta t} \tag{12}$$

In this equation, α_c is the maximum battery charge rate in A/Ah and Q_{max} is the total capacity of the battery in kWh. There is also a third limitation related to the maximum battery charge current:

$$P_{batt,cmax,mcc} = \frac{N_{batt}\ I_{max}\ V_{nom}}{1000} \tag{13}$$

In this equation, N_{batt} is the number of batteries, I_{max} is the maximum battery current in A, and V_{nom} is the nominal voltage in V. Therefore, the maximum battery capacity will be equal to the minimum of the aforementioned values:

$$P_{batt,cmax} = \frac{Min(P_{batt,cmax,kbm},\ P_{batt,cmax,mcr},\ P_{batt,cmax,mcc})}{\eta_{batt,c}} \tag{14}$$

Here, $\eta_{batt,c}$ is the battery charging efficiency. In this study, it was assumed that the system will use a 4 kS25P battery with a nominal voltage of 4 V and a nominal capacity of 1900 A.h. Table 1 shows the specifications of this battery. To optimize the number of batteries, this number was changed from 0 to 100 in steps of 10.

In this study, the average electricity demand in the region is estimated. In addition, due to the variability of electricity demand in each region, a 10 kw step has been considered for the size of energy systems, which is an optimization step in other studies in rural areas [50,51].

The price of solar panels has been selected based on previous studies, especially recent studies in Iran. For example, the price of $6900 for solar panels is considered based on a study [51–53] in a village in western Iran and a village in eastern Iran.

In the present study, energy generators such as diesel, wind turbines, and solar panels are generally selected, and the results presented in the present study are not limited to a specific type of diesel, wind turbine, or solar panel. Therefore, the purpose of this study is the size of energy generators.

Table 1. Specifications of the components of the proposed system.

System Components	Parameters	Value
Solar PV [51–53]	Operational lifetime	25 Years
	Ground reflectance	20%
	Capital cost per KW	$6900
	Replacement cost	$6900
	O & M cost per year	0
	Derating factor	90%
	Sizes considered	0–100 kW
Wind turbine (BWC XL. 1) [51]	Operational lifetime	25 Years
	Capital cost per KW	$1900/kW
	Replacement cost	$1900/kW
	O & M cost	$48/year
	Size considered	0–100 kW
Converter [51–53]	Operational lifetime	15 years
	Capital cost per KW	$800/kW
	Replacement cost	$700/kW
	Efficiency	95%
	Size considered	0–100 kW
Diesel generator [51–53]	Operational lifetime	15,000 h
	Capital cost per KW	$3500
	Replacement cost	$3500
	O & M cost	$0.023/h
	Minimum load ratio	30%
	Size considered	0–100 kW
Battery [2]	Operational lifetime	12 years
	Capital cost per KW	$1000
	Replacement cost	$800
	O & M cost	$10
	Size considered	0–100 unit

3.9. Economic Assessment

The economic efficiency of the considered energy system was defined as how much it costs in terms of *LCOE* and *NPC* to meet the estimated electricity demand. These parameters were calculated as follows. The real interest rate, i, was calculated based on the nominal interest rate, i', using the following relation:

$$i = \frac{i' - f}{i + f} \tag{15}$$

where f is the annual inflation rate. This rate was considered to be constant throughout the period of interest. The total *NPC* was obtained by dividing the total annual cost by the capital recovery factor (*CRF*), which is given by the following equation:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{16}$$

where N is the lifetime of the project and $C_{ann,tot}$ is the total cost. Therefore, *NPC* can be calculated as follows:

$$NPC = \frac{C_{ann,tot}}{CRF(i,N)} \tag{17}$$

LCOE or in other words the price of each kilowatt-hour of electricity generated was calculated as follows:

$$LCOE = \frac{C_{ann,tot}}{E_{\ prim,AC}} \tag{18}$$

where $E_{prim,AC}$, AC is the AC power consumed. The values of economic parameters considered in this study are given in Table 2.

Table 2. Input economic parameters.

Parameters	Value
Project lifetime	25 Years
Diesel price [54]	0.102 $/L
Annual real interest rate [51]	18%

3.10. Renewable Fraction (RF)

The renewable fraction or RF refers to the fraction of total electricity that is produced by renewable sources (rather than the diesel generator) [2]. The renewable fraction is the ratio of total renewable power produced by renewable energy sources to total power generated by the entire system. This fraction was calculated as follows:

$$RF(\%) = \left(1 - \frac{\Sigma P_{diesel}}{\Sigma P_{renewable}}\right) \times 10 \tag{19}$$

where P_{diesel} is the power output of the diesel generator and $P_{renewable}$ is the power output of renewable sources (wind and solar) of the considered system.

3.11. Emission

Considering the presence of a conventional generator as a backup source in the assumed energy system, the environmental impact of this component had to be considered. Since this generator was assumed to be running on diesel, its CO_2 emission was considered to be 2.62 kg per liter of diesel.

3.12. Sensitivity Analysis

The use of diesel generators is one of the most common ways of bringing electricity to remote areas that lack access to power networks. However, the government provides a limited amount of subsidized diesel fuel to remote villages, which means the inhabitants of these settlements need to also use firewood to meet their energy needs. Furthermore, the expense of transporting fuel to remote areas will increase the overall cost to the point that diesel as a sole source of energy is no longer feasible. The current price of diesel in urban areas of Iran is approximately 0.102 $/L and can be slightly higher in rural areas because of transportation costs. While this price is one of the lowest in the world, recent years have seen significant fluctuations in the price of this fuel [15]. Therefore, a sensitivity analysis was also performed to determine the sensitivity of the results to the price of diesel fuel. This sensitivity analysis was conducted by considering a 15% increase in the current price, a 30% increase in the current price, and also a return to the highest recent price, which was 0.202 $/L in 2016 [15].

Since the study was focused on the use of renewable energy sources, another sensitivity analysis was also performed to determine the sensitivity of the results to the output of renewable sources. This analysis was conducted by assuming a 15% or 30% decrease in solar radiation and a 15% or 30% decrease in wind speed and examining the effect on the performance of the optimized system, especially the price of electricity per kilowatt-hour.

3.13. Multi-Criteria Decision-Making Methods

Multi-criteria decision-making the process of selecting the most appropriate solution from a set of available options is based on a set of criteria [55–57]. One of the reasons for using the SWARA method is the use of less comparative data due to the lack of complete pairwise comparisons [58,59]. The most important advantage of this method compared to other similar methods is its ability to evaluate the accuracy of experts' opinions about the weight indicators given during the method process [60,61]. The WASPAS method is based on a combination of two models, a combination of the WSM method and the WPS method, which can be highly efficient in complex decision-making problems, and also the results of this model are highly accurate [62]. The reasons for their novelty are the simplicity of the process of performing these methods, as well as the fact that these methods lead to more robust comparisons, which means that they give more reliable answers than other weighting methods. Multi-criteria decision-making methods have been used to select options in the field of energy [63–65].

Stepwise Weight Assessment Ratio Analysis (SWARA)

Keršuliene et al. developed the SWARA approach in 2010, and one of the weighting methods is criteria, which is more reliable than other weighting methods because it can determine the accuracy of experts' views on the weight of criteria [66]. Sorting the criteria, deciding the relative value of each criterion, measuring the relative importance of each criterion, calculating the local weight of each criterion, and determining the final weight of each criterion are all stages in the SWARA process [66].

Weighted Aggregated Sum Product Assessment (WASPAS)

Zavadaskas developed WASPAS, a new decision-making method, in 2012 [67]. It integrates the weight sum model (WSM) and the weighted product model (WPM), resulting in a model that is both efficient and effective in solving complex problems [67].

Stage 1: Form an $m \times n$ matrix as follows:

$$x = \begin{bmatrix} x_{01} & \dots & x_{0j} & \dots & x_{0n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & \dots & x_{ij} & \dots & x_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{m1} & \dots & x_{mj} & \dots & x_{mn} \end{bmatrix} \quad i = \overline{0,m};\ j = \overline{1,n} \tag{20}$$

When unknown, x_{0j} can be defined as follows:

$$\begin{aligned} x_{0j} &= \max_i x_{ij}, && \text{if } \max_i x_{ij} && \text{is preferable} \\ x_{0j} &= \min_i x^*_{ij}, && \text{if } \min_i x^*_{ij} && \text{is preferable} \end{aligned} \tag{21}$$

It should be noted that the first step of the criteria may have different dimensions.

Stage 2: Normalize the primitive input values of all criteria and convert into the matrix $\bar{x}$.

$$\bar{x} = \begin{bmatrix} \bar{x}_{01} & \dots & \bar{x}_{0j} & \dots & \bar{x}_{0n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \bar{x}_{i1} & \dots & \bar{x}_{ij} & \dots & \bar{x}_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \bar{x}_{m1} & \dots & \bar{x}_{mj} & \dots & \bar{x}_{mn} \end{bmatrix} \quad i = \overline{0,m};\ j = \overline{1,n} \tag{22}$$

For positive criteria, normalization is done using Equation (23):

$$\bar{x}_{ij} = \frac{x_{ij}}{\max_i x_{ij}} \tag{23}$$

For negative criteria, normalization is done using Equation (24):

$$x_{ij} = \frac{\min_i x_{ij}}{x^*_{ij}} \tag{24}$$

Stage 3-A: The normalized decision matrix for WSM is calculated:

$$\hat{X}_q = \begin{bmatrix} \hat{x}_{11} & \dots & \hat{x}_{1j} & \dots & \hat{x}_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \hat{x}_{i1} & \dots & \hat{x}_{ij} & \dots & \hat{x}_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \hat{x}_{m1} & \dots & \hat{x}_{mj} & \dots & \hat{x}_{mn} \end{bmatrix}; \hat{x}_{ij} = \overline{x}_{ij} w_j,\ i = \overline{1, m};\ j = \overline{1, n} \tag{25}$$

Stage 3-B: The normalized decision matrix for WPM is calculated:

$$\overline{\overline{x}}_p = \begin{bmatrix} \overline{\overline{x}}_{11} & \dots & \overline{\overline{x}}_{1j} & \dots & \overline{\overline{x}}_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \overline{\overline{x}}_{i1} & \dots & \overline{\overline{x}}_{ij} & \dots & \overline{\overline{x}}_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \overline{\overline{x}}_{m1} & \dots & \overline{\overline{x}}_{mj} & \dots & \overline{\overline{x}}_{mn} \end{bmatrix}; \overline{\overline{x}}_{ij} = \overline{x}_{ij}{}^{w_j},\ i = \overline{1, m};\ j = \overline{1, n} \tag{26}$$

Stage 4: The values of WSM, WPM, and WPS_i are calculated.
(A) According to WSM, for each alternative:

$$Q_i = \sum_{j=1}^{n} \hat{x}_{ij}, i = \overline{1, m} \tag{27}$$

(B) According to WPM, for each alternative:

$$P_i = \sum_{j=1}^{n} \overline{\overline{x}}_{ij}, i = \overline{1, m} \tag{28}$$

Step 5: A score for the ranking of alternatives is calculated using Equation (29):

$$WPS_i = 0.5 \sum_{j=1}^{m} Q_i + 0.5 \sum_{j=1}^{m} P_i \tag{29}$$

In WASPAS, the alternatives are ranked based on their WPS_i.

4. Results and Analysis

4.1. Potential of Renewable Energy Sources

Figure 6 shows the amount of solar radiation received in the study area. As can be seen, thanks to its suitable geographical location, this area has a good potential for harvesting solar radiation. The daily solar radiation received in this area is averagely 5.6 kWh/m^2/day, with the highest amount, 7.19 kWh/m^2/day, occurring in May and the lowest, 3.59 kWh/m^2/day, occurring in December.

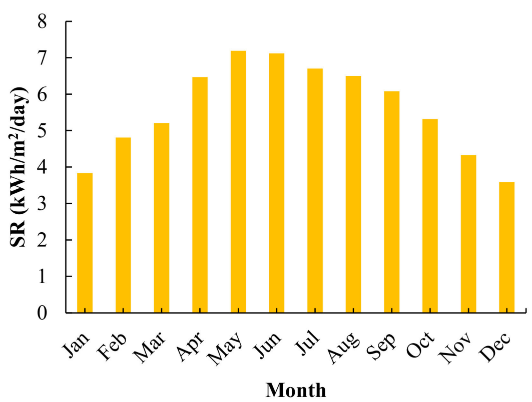


Figure 6. Changes in the solar radiation received in the Bostegan village.

Figure 7 shows the cloudiness of this area. The highest cloudiness index, 0.665, belongs to October, and the lowest, 0.569, belongs to March. The average cloudiness index of the area is 0.62. As can be seen, there is no substantial change in the cloudiness of the area.

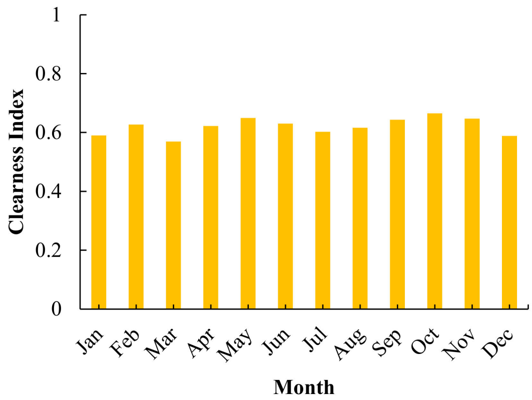


Figure 7. Changes in the cloudiness index of the Bostegan village.

Figure 8 shows the changes in monthly wind speed at a height of 10 m in the study area. The highest monthly wind speed is 3.51 m/s, which occurs in February, and the lowest is 2.99 m/s occurring in September. The average wind speed in the study area is 3.23 m/s. While the moderate wind energy potential of the area make it ill-suited for building large turbines (with high hub height), the flat shape of wind speed distribution means that wind turbines will have an almost uniform electricity output, which is very desirable for wind power generation projects (a bell-shaped wind speed distribution may cause the system to experience severe output drops [15]).

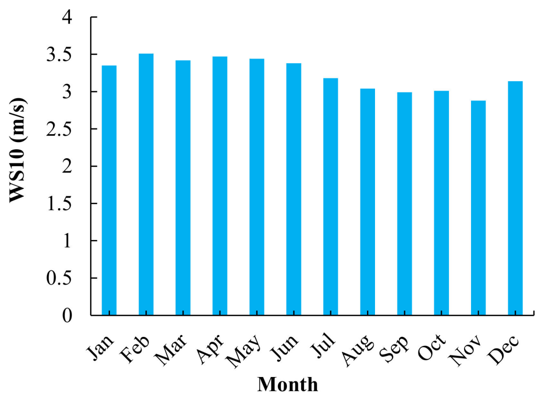


Figure 8. Changes in the monthly wind speed at a height of 10 m in the Bostegan village.

4.2. Optimization of System Configuration

The HOMER software was used to search for the best configurations for the components of the assumed energy system. After checking a total of 161,051 configurations, the ones given in Table 3 were identified as the top eight choices.

Table 3. Top configurations for the assumed energy system.

Configuration	PV (kW)	WT (kW)	DG (kW)	BT (Unit)	CV (kW)	Initial Cost ($)	Operating Cost ($/Year)	NPC ($)	LCOE ($/kWh)	RF (%)
PV–WT–DG–BT–CV	10	20	20	20	10	$205,000	14,583	$284,724	1.058	0.64
WT–DG–BT–CV		20	20	10	10	$126,000	29,695	$288,338	1.072	0.29
PV–DG–BT–CV	10		20	10	10	$157,000	24,391	$290,343	1.079	0.37
DG			20			$70,000	45,253	$317,394	1.18	0
WT–DG		10	20		10	$97,000	46,622	$351,877	1.308	0.12
PV–WT-BT–CV	30	20		70	20	$331,000	5309	$360,023	1.338	1
PV–DG–CV	10		20		10	$147,000	44,187	$388,569	1.444	0.27
PV-BT–CV	40			80	20	$372,000	4656	$397,453	1.478	1

As Table 3 shows, the best system configuration was found to be the simultaneous use of wind and solar energies with a diesel generator and batteries attached to an inverter acting as support components. The second-best system was WT–DG–BT–CV, and the third-best was PV–DG–BT–CV. Because of the cheapness of diesel fuel in Iran, the fourth-best solution is to just use a diesel generator. However, the use of renewable energy sources alongside the diesel generator reduces not only the system cost but also its environmental impact. The fifth-, seventh-, and eighth-best configurations in terms of economic feasibility were WT–DG, PV–DG–CV, and PV–BT–CV, respectively. While these configurations have been able to meet the assumed electricity demand with one or two fewer components, even better results have been obtained with those components present in the system. For example, while the fifth-best configuration has no battery or converter, adding these components to the same configuration makes it the second-best choice. Certain configurations such as PV–DG are completely absent from Table 3, which is because they cannot meet the assumed demand. It can also be seen that the cleanest configuration, i.e., the one with wind–solar energy sources combined only with a converter and a battery (without a diesel generator), can meet the assumed demand and is ranked sixth in terms of feasibility. Based on these results, in the remainder of the study, the following four scenarios were used as the basis of analyses:

1- Scenario I: using the PV–WT–DG–BT–CV system,
2- Scenario II: using the WT–DG–BT–CV system,
3- Scenario III: using PV–DG–BT–CV system,
4- Scenario IV: using the PV–WT–BT–CV system.

4.3. Economic Assessment

One of the most important parts of any energy project assessment is the economic analysis of its cost flows. According to the results presented in Table 3, among the four considered scenarios, Scenario I has the lowest NPC and LCOE at $284,724 and 1.058 $/kWh, and Scenario IV has the highest NPC and LCOE at $360,023 and 1.338 $/kWh, respectively. The purpose of cost flow analysis is to identify the cause of such differences. Figure 8 shows the cost flow of the system in the four scenarios. As the figure shows, in Scenario I, the system makes use of all defined components, i.e., solar panels, wind turbine, diesel generator, battery, and converter. Thus, as can be expected, this scenario has the highest initial cost among all scenarios (see Table 3). In Scenarios II, III, and IV, however, the cost flow for the components that are not used in the system (i.e., solar panel in Scenario II, wind turbine in Scenario III, and diesel generator in Scenario IV) is zero. As shown in Figure 9, there is no significant difference between the first three scenarios in terms of the costs of most system components, including converter, battery, and renewable sources (there is no significant difference between the first and second scenarios in terms of the cost of the wind source or between the first and third scenarios in terms of the cost of the solar source). Although Scenario I uses all the considered components and is more expensive than Scenario II and Scenario III in terms of renewable sources, the cost of using both renewable sources in this scenario is far lower than the cost arising from the increased use of the diesel generator in the other two scenarios. In Table 3, it can be seen that there is no difference between the first three scenarios in terms of the capacity of the diesel generator, which means the observed cost differences are related to how much this generator is used. In other words, the presence of both solar and wind sources in the system of Scenario I has allowed it to rely more on these sources and less on the diesel generator, which has resulted in lower operating costs. As shown in Table 3, the operating costs for Scenarios I, II, and III were estimated to \$14,583, \$29,695, and \$24,391, respectively. The completely clean system of Scenario IV has a much higher cost than these three scenarios. While this system has no diesel generator and therefore no diesel-related cost, it needs to use high-capacity renewable systems with larger batteries to compensate for the absence of the diesel generator, and this makes it much more expensive than other scenarios.

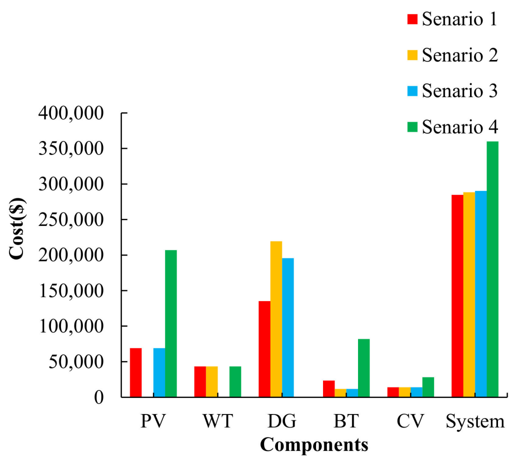


Figure 9. Cost flow of the systems in the four top scenarios by the components included in theconfiguration.

For a more accurate assessment, the cost flows of the four scenarios by the type of cost are illustrated in Figure 9. In Figure 10, it can be seen that among the first three scenarios, Scenario I has the highest initial cost (as it requires more equipment), but Scenario II and Scenario III have a higher replacement cost, indicating that they may not be economically viable in the long run. Although Scenario IV does not use a diesel generator, which results in having far lower replacement and fuel costs, it requires much more expensive renewable energy generation and storage equipment, which greatly increases its initial cost, making it the most expensive among the four scenarios.

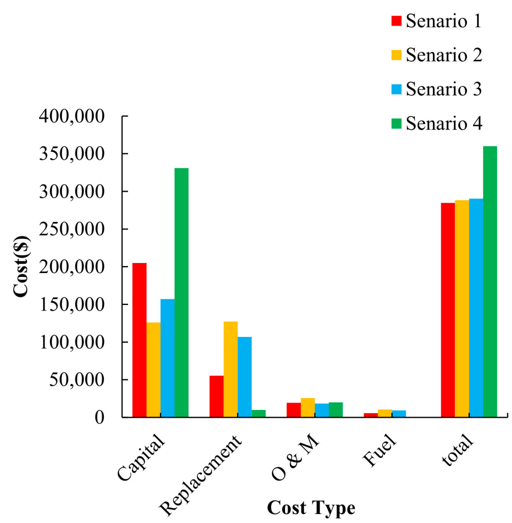


Figure 10. Cost flow of the systems in the four top scenarios by the type of cost.

4.4. Environmental Assessment

Another goal of the present study was the environmental assessment of the considered project. One of the most important measures of environmental impact is the RF index, which quantifies the renewability of the proposed system. This measure is plotted in Figure 11. As expected, the RF index of the system of Scenario IV (without diesel generator) is 100%. For the system of Scenario I, which uses two renewable energy sources, this index is 64%. The main determinant of this is the fraction of total power that is produced by burning diesel as fuel.

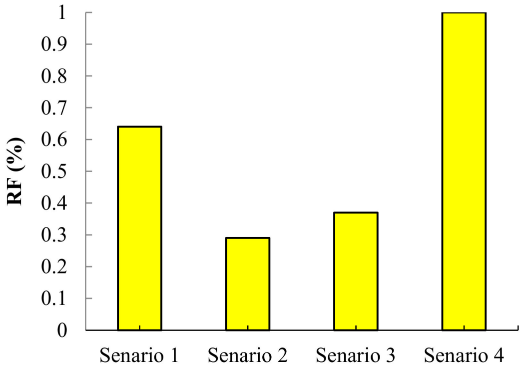


Figure 11. RF index in different scenarios.

For a closer assessment of this index, the amount of diesel consumed in the four scenarios is plotted in Figure 12. As expected, the lowest fuel consumption is related to Scenario IV, which needs zero fuel. The second-lowest fuel consumption belongs to Scenario I, which needs 9902 L of fuel. The highest fuel consumption, 18,704 L, is related to Scenario II, which also has the lowest RF (29%) among the four scenarios (see Figure 10).

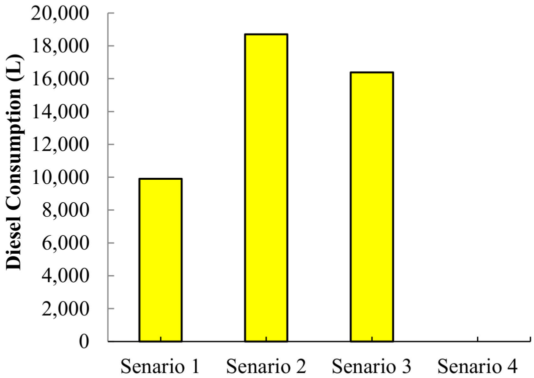


Figure 12. The amount of diesel fuel consumed in different scenarios.

The amount of fuel consumed also determines the environmental impact of the system in terms of emission. The most important emission is CO_2, the plot of which is presented in Figure 13. As expected, the highest CO_2 emission, 49.25 ton/yr, was found to be related to Scenario II, and the lowest, zero, was related to Scenario IV (the one without a diesel generator). The CO_2 emission of Scenario I was estimated to be 26.07 ton/yr.

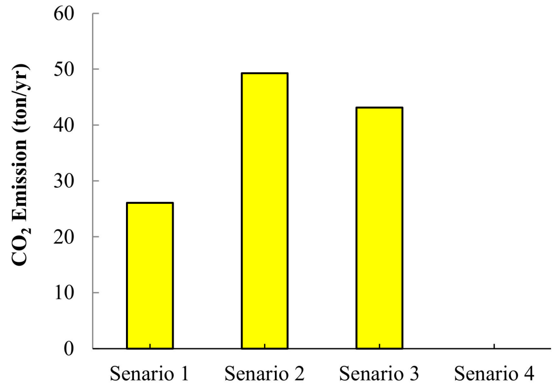


Figure 13. CO_2 emission due to fuel consumption in different scenarios.

4.5. Selecting the Best Scenario Using MCDM Methods

In this step, to select the best scenario, SWARA–WASPAS hybrid methods are used. The SWARA method is used to weight the criteria, and the WASPAS method is used to rank the scenarios. The identified criteria are weighed according to the SWARA method, the weighting results of which are presented in Table 4.

Table 4. Results of weighting the criteria by SWARA method.

Criteria	Average Relative Importance	w_j	q_j	K_j
NPC	1	1	1	0.42
LCOE	0.6	1.6	0.625	0.263
Total investment	0.7	1.7	0.368	0.154
Replacement	0.76	1.76	0.209	0.088
RF	0.8	1.8	0.116	0.049
CO_2 (ton/yr)	0.86	1.86	0.062	0.026

In the following, the scenarios are ranked according to the steps of the WASPAS method. The results of ranking the scenarios are shown in Table 5. The results of scenario ranking showed that Scenario I was introduced as the best scenario.

Table 5. Scenario ranking results by WASPAS method.

City	Q_i	P_i	WPS_i	Rank
Scenario I	0.8257	5.6842	3.2550	1
Scenario II	0.8501	5.6349	3.2425	2
Scenario III	0.8203	5.6236	3.2220	4
Scenario IV	0.7615	5.7077	3.2346	3

4.6. Assessment of Electricity Generation in the Best Scenario

According to the ranking results by SWARA–WASPAS hybrid methods, the first scenario was considered the most appropriate scenario. Although Scenario IV was the best option in terms of environmental impact, Scenario I was found to provide an RF index of 64% at a much lower cost and with high reliability on account of having a diesel generator as the backup source. Therefore, after taking all factors into account, it was decided that Scenario I, i.e., the simultaneous use of the wind–solar sources with battery and converter and a diesel generator as backup, is superior to other top scenarios.

Figure 14 shows the electricity output of the three energy sources, namely solar, wind, and diesel, in Scenario I. As can be seen, the three energy sources have operated almost identically during the first months of the year. However, in the final months of the year, i.e., August, September, October, and November, the declining wind energy potential has resulted in deceased electricity output from wind turbines and therefore the diesel generator playing a greater role in the system.

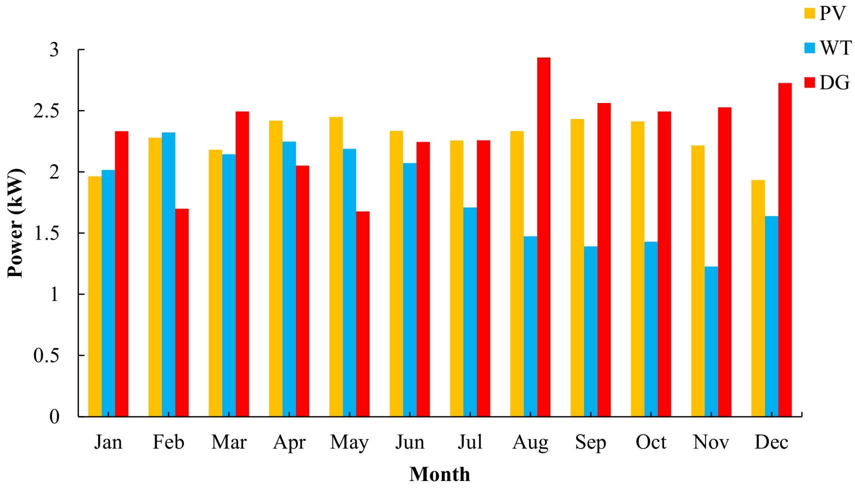


Figure 14. Electricity output in the best scenario (Scenario I).

4.7. Sensitivity Analysis

Following the approach of previous studies [9], a sensitivity analysis was performed to determine the sensitivity of the results to the fuel price and the renewable energy potential. This analysis involved calculating the results for three levels of fuel price (for the base price of 0.102 \$/L, for 30% higher price i.e., 0.133\$/L, and for the highest recent price i.e., 0.202\$/L), three levels of solar radiation (for the base radiation of 5.6 kWh/m^2/day, 15% lower solar radiation, i.e., 4.76 kWh/m^2/day, and 30% lower solar radiation, i.e., 3.92 kWh/m^2/day), and three levels of wind speed (for the base wind speed of 3.232 m/s, for 15% lower wind speed, i.e., 2.75 m/s, and for 30% lower wind speed, i.e., 2.262 m/s), which sum up to 27 parameter settings, as shown in Table 6. As can be seen, in the worst case, LCOE will change to 1.343 \$/kWh. Other changes in the results are shown in Table 6.

Table 6. Results of the sensitivity analysis performed on the best scenario.

Sensitive Code	SR (kWh/m^2/d)	WS10 m (m/s)	Diesel Price (\$/L)	Operating Cost (\$/yr)	NPC (\$)	LCOE (\$/kWh)	RF(%)
1	5.6	3.232	0.102	14,583	\$284,724	1.058	0.64
2	5.6	3.232	0.133	14,890	\$286,402	1.064	0.64
3	5.6	3.232	0.202	15,573	\$290,137	1.078	0.64
4	5.6	2.75	0.102	18,439	\$305,806	1.136	0.54
5	5.6	2.75	0.133	18,816	\$307,864	1.144	0.54
6	5.6	2.75	0.202	19,654	\$312,446	1.161	0.54
7	5.6	2.262	0.102	21,588	\$323,020	1.2	0.46
8	5.6	2.262	0.133	22,022	\$325,392	1.209	0.46
9	5.6	2.262	0.202	22,988	\$330,673	1.229	0.46
10	4.76	3.232	0.102	16,708	\$296,340	1.101	0.59
11	4.76	3.232	0.133	17,052	\$298,221	1.108	0.59
12	4.76	3.232	0.202	17,818	\$302,407	1.124	0.59
13	4.76	2.75	0.102	20,793	\$318,674	1.184	0.48
14	4.76	2.75	0.133	21,210	\$320,955	1.193	0.48
15	4.76	2.75	0.202	22,139	\$326,034	1.212	0.48
16	4.76	2.262	0.102	24,134	\$336,941	1.252	0.4
17	4.76	2.262	0.133	24,612	\$339,553	1.262	0.4
18	4.76	2.262	0.202	25,676	\$345,367	1.283	0.4
19	3.92	3.232	0.102	19,102	\$309,431	1.15	0.53
20	3.92	3.232	0.133	19,488	\$311,539	1.158	0.53
21	3.92	3.232	0.202	20,346	\$316,231	1.175	0.53
22	3.92	2.75	0.102	23,423	\$333,049	1.238	0.42
23	3.92	2.75	0.133	23,885	\$335,578	1.247	0.42
24	3.92	2.75	0.202	24,915	\$341,207	1.268	0.42
25	3.92	2.262	0.102	26,904	\$352,079	1.308	0.34
26	3.92	2.262	0.133	27,429	\$354,951	1.319	0.34
27	3.92	2.262	0.202	28,598	\$361,342	1.343	0.34

4.8. Hydrogen Production Potential

Although delivering electricity to the Bostegan village will resolve some problems of this village, the village may still become depopulated because of a lack of other welfare services and amenities (health and educational facilities, etc.). In this study, this possibility was also taken into consideration. Considering the multitude of studies conducted on hydrogen production in Hormozgan province, where this village is located, the proposed response to the depopulation of the village is to use renewable electricity to produce hydrogen. For this purpose, it is necessary to estimate the amount of electricity to be generated from renewable sources and then use the following equation to estimate the amount of hydrogen that can be produced by this electricity [4]:

$$H_2 = \frac{E_{WT,PV}}{Ec_{el}} \tag{30}$$

In this equation, $E_{WT,PV}$ is the amount of electricity generated is from wind and solar energy, and Ec_{el} is the amount of energy to be consumed during the electrolysis, which is about 5–6 kWh/m^3 [4].

The amount of power to be generated from renewable sources in the best scenario (Scenario I) is shown in Figure 15. As can be seen, the system consisting of 10 kW solar panels and a 20-kW wind turbine with a 10-kW converter will produce 35,786 kWh of power each year. Of this amount, approximately 19,854 kWh/year or 55% will be produced by solar panels, and the rest will be generated by the wind turbine.

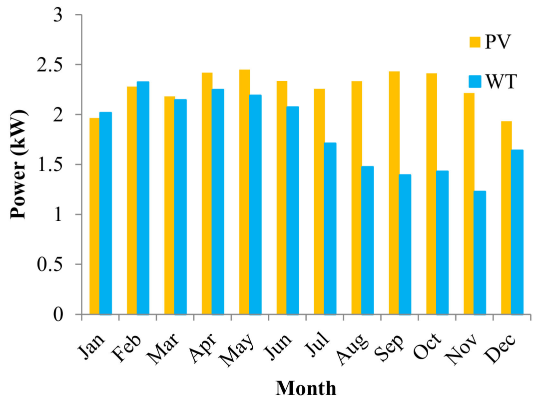


Figure 15. Power output of the assumed renewable sources.

The amount of hydrogen to be produced with this amount of renewable electricity is shown in Figure 16. Overall, the average annual hydrogen output in this region will be 643.63 ton/year.

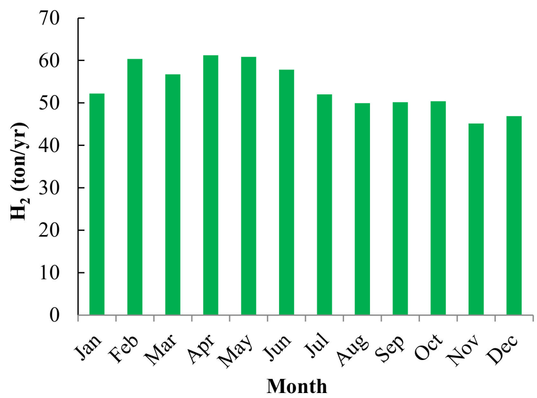


Figure 16. Hydrogen production from the power output of the assumed renewable sources.

Due to the elimination of diesel generators and batteries in this scenario, costs have been greatly reduced. In general, the amount of NPC in this scenario was equal to 126,262$. Additionally, the amount of electricity generated in this scenario was equal to 35,786 kWh per year, so the cost of electricity consumption or the LCOE index was equal to 0.74 $/kWh. To calculate the price of hydrogen produced, the levelized cost of hydrogen ($LCOH$) method was used, which is as follows [68]:

$$LCOH\left(in\frac{\$}{kg}\right) = \frac{C_{electrolyzer} + C_{electricity}}{M_{hydrogen}} \tag{31}$$

where the denominator of the fraction represents the total amount of hydrogen produced per year. $C_{electricity}$ is equal to the cost of electricity consumed by the electrolyzer unit, and $C_{electrolyzer}$ is equal to the total cost of the electrolyzer unit per year and is calculated as follows:

$$C_{electricity} = LCOE \times E_{consumption} \tag{32}$$

$$C_{electrolyzer} = C_{u.\ electrolyzer} \times Size_{electrolyzer} \times CRF \times 8760 \tag{33}$$

where $C_{u.\ electrolyzer}$ is the unit price of the electrolyzer.

Because the average output power of the set was equal to 4.085 kW, and as shown in Figure 15, the maximum output power was less than 5 kW, so the electrolyzer with a nominal capacity of 5 kW had been used. The cost of the electrolyzer unit is $384/kW according to the [13]. Therefore, considering that the cost of electricity consumption per year was equal to $26,515.02, the cost of electrolyzer per year was equal to $3,532,032, the amount of hydrogen production per year was equal to 643,630 kg, and the LCOH index was equal to 5.53 $/kg-H2. This value is also compared with values in different countries and is shown in Table 7. As it was known, this proposed scenario is cost-effective and fully feasible.

Table 7. Compare prices LCOH in different countries.

Research	Case Study	Resource	LCOH
Viktorsson, Heinonen [69]	Halle, Belgium	Wind–solar–grid	10.3 €/kg
Gökçek and Kale [70]	İzmir-Çeşme, Turkey	Wind–solar	7.526–7.866 $/kg
Moser, Pecchi [71]	Almeria, Spain	Solar–CSP	13.06–38.83 €/kg
Moraes, Cozendey da Silva [72]	Brazil	Ethanol fuel processor	8.87 $/kg
Minutillo, Perna [73]	Italy	Solar–PV	9.29–12.48 €/kg
Niaz, Lakouraj [74]	Korean	Solar–PV	9.55–11.67 $/kg
Present scenario	Remote area in Iran	Wind–solar	5.53 $/kg

To consider Potential Induced Degradation, it is recommended to use quality panels with PID test under IEC62804 standard [75], because the quality of the cell and the quality of panel production affect the possibility of this phenomenon. Additionally, for solar power plants in use, it is possible to use equipment that creates a reverse voltage to neutralize the electric field created and reduce this phenomenon to or close to zero.

In the case of battery disposal, unusable batteries are transferred to recovery and recycling centers to return to the consumption cycle by recycling and recycling, reducing the harmful effects of battery disposal, and improving the sustainability of the battery chain.

5. Conclusions and Recommendations

This study investigated the feasibility of using an HRES consisting of wind turbine and solar panels as renewable sources and a support system comprised of a converter, a battery unit, and a diesel generator to power the buildings of a remote village in Hormozgan province, Iran. Technical, economic, and environmental assessments were performed using the HOMER software, and the best system configuration was selected accordingly, with NPC and LCOE used as selection criteria. The study also investigated another scenario in which the village is depopulated (because of the lack of other services), and the government investment in the area's renewable power potential is used to produce hydrogen instead of powering buildings. A summary of the most important results of the study is provided below:

- The most suitable system configuration was found to be the one consisting of all defined components, specifically solar panels with a capacity of 10 kW, a wind turbine with a capacity of 20 kW, a converter with a capacity of 10 kW, 20 batteries, and a diesel generator with a capacity of 20 kW. For this configuration, NPC and LCOE were estimated to be $284,724 and 1.058 $/kWh respectively.
- The highest LCOE, 1.478 $/kWh, was related to the scenario in which no diesel generator was used, a result that can be attributed to the low price of diesel fuel in Iran and the necessity of using larger more expensive equipment in the renewable sub-systems of HRES to meet the demand without the diesel generator.
- The renewable fraction (RF) of the proposed PV–WT–CV–DG–BT system is 64%, and it consumes 19,175 L (approximately 34%) less fuel than the diesel system.
- The first scenario, i.e., the simultaneous use of the wind–solar system with a battery and converter and diesel generator support system, was recognized as the best scenario using SWARA–WASPAS hybrid methods.
- The results of sensitivity analysis showed that an increase in the price of diesel or a decrease in the area's renewable energy potential will increase the final price of electricity (at worst, LCOE = 1.343 $/kWh), but the proposed system can still meet the demand of the region with high reliability.
- If the village becomes depopulated, the government can use the investment in the area's renewable potential to produce hydrogen for the refineries of Hormozgan province. The hydrogen production potential of this area is about 643.63 ton-H2/year.

In future studies, researchers can apply the method of the present study to perform similar analyses for other underdeveloped areas in Iran as well as neighboring countries, especially Afghanistan, which still lack access to electricity grids. The use of multi-criteria decision-making methods to select the type of optimal power generation system is an attractive topic for research. Considering more criteria and parameters for reviewing and selecting the optimal power generation system is another area of research. Access to more data and data validation to examine parameters and systems of energy production are other areas of research.

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