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Techno-Economic Analysis and Optimization of an Off-Grid Hybrid Photovoltaic–Diesel–Battery System: Effect of Solar Tracker

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Abstract: Increment in energy demand, limitation of fossil fuels and fluctuations in their price, in addition to their pollution, necessitate development of renewable energy systems. Regarding the considerable potential of solar energy in Iran, this type of renewable energy has developed more compared with other renewable energies. Hybrid technologies consisting of photovoltaic (PV) cells, diesel generator, and battery are one of the efficient solutions to resolve the issues related to the energy supply of rural areas. In this study, a hybrid PV/diesel/battery system composed of the mentioned components is applied to supply the off-grid power with capacity of 233.10 kWh/day with peak load of 38.38 kW in a rural region in South Khorasan, Iran. The purpose of this study is to reduce the net present cost (NPC), levelized cost of energy (LCOE), CO_2 reduction, renewable fraction (RF) enhancement and increase reliability. In order to improve the performance of the system, different tracking system, including fixed system, horizontal axis with monthly and continuous adjustment, vertical axis with continuous adjustment and two-axis tracker, are analyzed and assessed. The results indicate that the vertical axis with continuous adjustment tracker is the most suitable option in terms of economic and technical requirements. In this work, a sensitivity analysis is performed on different parameters such as PV cost, interest rate, diesel generator cost, battery cost, and price of fuel, and the outcomes reveal that the hybrid system with vertical axis continuous adjustment is very sensitive to costs of fuel and the battery, i.e., NPC decreases by 5% in case of 20% variations in costs of battery and fuel. In addition, it is found that diesel generator and inverter costs significantly influence NPC of the system.

Keywords: hybrid energy systems; PV/diesel/battery; solar tracking system; optimization; sensitivity analysis

1. Introduction

Currently, most of the world energy demand is supplied by fossil fuels such as oil products, coal, and natural gas [1]. There are several problems related to the utilization of these fuels such as fluctuations in their price, greenhouse gas emission, and limitation in their resources [2–4]. Increase in the cost and the economic challenges related to excessive use of fossil fuels has caused more attention to the renewable energy sources [5–7]. Different renewable energies such as hydropower, solar, biofuels, geothermal, and wind are applicable for supplying the required energy of human activities. Among the renewables, solar energy is the most abundant one [8–10]. Iran, with around 300 sunny days per year in more than 2/3 of its region and mean radiation of more than 5 kWh/m^2·day, is introduced as one of the countries with considerable potential in terms of solar energy. These features make solar energy for power generation an efficient solution for supplying annual energy demand and dependency on fossil fuels [11]. Regarding the economic subjects such as the cost of network, fuel price, transmission cost, and hard-to-reach geographical areas, it is not possible to install proper infrastructure in remote rural areas and connect them to the grid. In these cases, applying solar technology for power supply is an appropriate way to produce power from renewable energies [12,13]. Some renewable energy technologies such as photovoltaic (PV) cells are not able to produce power in a continuous way and require a backup system in order to supply the power in case these systems are not active or produce power inadequately. To resolve the issues related to the fluctuations in the energy sources, different hybrid energy systems, composed of two or more technologies, are applied; furthermore, these systems are able to decrease the levelized cost of energy (LCOE) and emission of greenhouse gases [14–16]. Hybrid Energy Systems have been modeled and optimized for different purposes [17–21], while the ones composed of PV cells and storage units are very conventional for the residential sector [22].

Several studies have been conducted to obtain the optimal size and cost of components. Yahiaoui et al. [23] investigated a new approach for optimization of a hybrid system. They applied multi-objective particle swarm optimization in their work by coupling MATLAB and HOMER software and concluded that a combination of both PV cells and diesel generator is required in order to provide the energy lack of a rural region. Amutha et al. [24] investigated the industrial, domestic, and agricultural base transceiver station loads in a remote village located in India and found that solar, wind, hydropower, and battery is the most optimal cost–benefit combination in term of economics and the environment. Pal et al. [25] analyzed three different architectures based on renewable energies including PV-alone, wind-alone, and PV-wind systems for a region in India. Their findings revealed that the hybrid system is appropriate for their case study. Muh and Tabet [26] investigated the use of different renewable energy systems for generation of power in Southern Cameroons by considering weather data. They indicated that the hybrid system composed of diesel generator, battery, PV, and small hydropower has the lowest net present cost (NPC) and LCOE. Talavera et al. [27] investigated fixed, single-axis, and horizontal two-axis trackers for different regions and with various configurations by considering economic and technical parameters. They concluded that the best scenario on the basis of the LCOE did not denote profitability. They expressed that under certain condition, with the same LCOE, single-axis systems are the best options. Mohammadi et al. [28] investigated the potential of development of grid-connected PV power plants using trackers in eight cities in the southern region of Iran. They found that development of plants in all of the cities is useful and applying single-axis systems is the most cost-effective option. Li and Yu [29] indicated that economic and environmental factors significantly influence the selection of off-grid tracking systems. Their results indicated that increase in interest rate causes a decrease in NPC and greenhouse gas costs. Sinha and Chandel [30] investigated power generation by considering different configurations with fixed-tilt and tracking system in India. They concluded that the findings could not be developed for other cases and are valid for the considered case study based on the corresponding weather data. Shabani and Mahmoudmehr [31] performed technical and economic assessment on PV trackers for a system in a region in the south of Iran and found that an azimuth tracking system with fixed-tilt angle leads to the minimum costs. Hammad et al. [32] compared the economic parameters of grid-connected PV systems and concluded that the annual production of the system with tracking was 31.29% higher than the fixed system. Singh et al. [33] analyzed different solar tracking systems and concluded that two-axis systems have better performance compared with single-axis ones. Awasthi et al. [34] analyzed PV cells and different tracking systems and indicated that the two-axis tracker is more efficient in comparison with the fixed and single-axis ones.

According to previous studies, it can be denoted that several pieces of software and algorithms with different objective functions have been applied to analyze and evaluate the hybrid systems composed of battery, diesel generator and PV cell used in remote rural areas; however, there are few studies that have considered the effects of tracker type on the performance of the systems and performed sensitivity analysis on these systems.

The main contributions of this study are as follows: a hybrid system composed of battery, PV cells, and diesel generator applied for power supply in a specific region is modeled and investigated. To improve the output of this system, different types of trackers including fixed, horizontal axis (with monthly and continuous adjustment), vertical axis (continuous adjustment) and two-axis tracker are applied. The aim of the modeling is analysis of the system in term of reliability, cost reduction, decrement in LCOE and increase in Renewable Fraction (RF); moreover, the sensitive parameters of this system are to be distinguished and assessed.

In the next section of the study, the model of each component is explained. Afterwards, the objective function and optimization are introduced. Subsequently, results and discussion are provided and finally, the conclusion is represented.

2. Mathematical Model

In this work, a hybrid system composed of battery, PV panel, and Diesel Generator (DG) is applied which is shown in Figure 1. As shown in Figure 1, there are two buses, including AC (alternative current) and DC (direct current), which connect the system via inverter. DC is connected to the AC bus, while battery and PV are linked to the DC bus. Since the consumed energy is alternating current, the load is linked to AC bus. The aim of the study in the first stage is to analyze the effect of five tracking systems on the NPC and LCOE and subsequently performing sensitivity analysis.

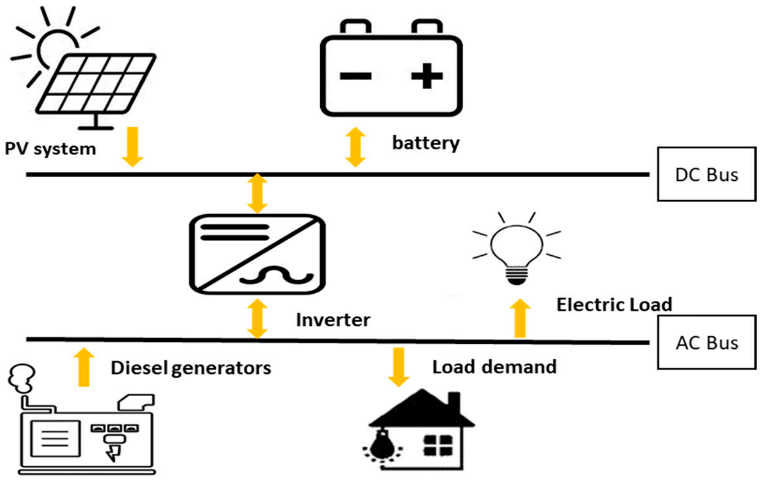

Figure 1. The hybrid system schematic.

2.1. PV Power

For accurate modeling of the hybrid system with PV cells, it is necessary to have hourly solar radiation. By using Equation (1), the generated power by each PV panel, which is under the influence of temperature and radiation, can be determined [35,36].

$$P_{PV} = R_{PV}\,F_{PV}\left(\frac{G_T}{G_{T,STC}}\right) \quad (1)$$

where R_{PV}, F_{PV}, G_T, and $G_{T,STC}$ are rated capacity (kW), PV derating factor (%), solar radiation (kW/m^2), and standard solar radiation (kW/m^2), respectively.

PV Tracker

The majority of the PV panels are installed on fixed systems which receive the most energy in midday hours. These systems have some advantages in terms of simplicity of the structure and cost; however, tracking systems are able to produce greater power in other hours. In this regard, the main advantage of tracking system is their ability in receiving solar energy in the highest duration in a day. Tracking systems are categorized based on their rotating axes, which are shown in Figure 2. Six tracking systems are explained as follows [11]:

- Horizontal Axis with Monthly Adjustment (HTMA): Axis of rotation is from east to west and the tilt angle is tuned in each month in order to make it in the positions which are near vertical to the solar radiation in midday time.
- Horizontal Axis with Weekly Adjustment: Around horizontal axis rotation has occurred and the angle is tuned each week.
- Horizontal Axis with Daily Adjustment: Around horizontal axis the rotation has occurred, and the angle is adjusted each day.
- Horizontal Axis with Continuous Adjustment (HTCA): These trackers rotate around the horizontal axis and the angle is continuously tuned.
- Vertical Axis with Continuous Adjustment (VTCA): The system is continuously rotated around the vertical axis (north to south), while the tilt angle is constant.
- Two-Axis with continuous Adjustment (DTCA): The surfaces continuously rotate around both axes to keep the vertical angle between the panels and solar radiation.

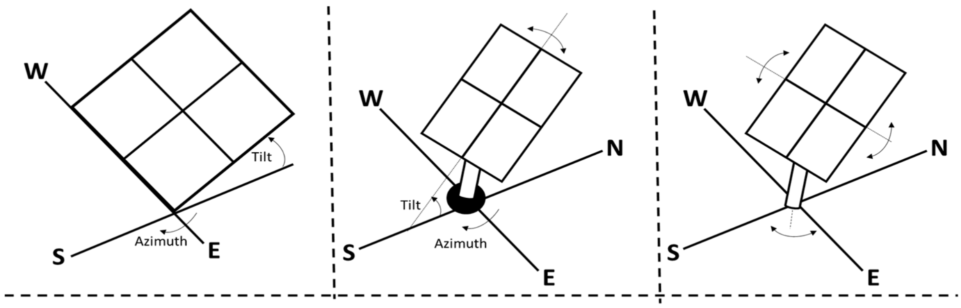

Figure 2. Different types of solar trackers.

In this article, four famous tracking systems are examined, namely, HTMA, HTCA, VTCA, and DTCA.

2.2. Diesel Generator

Conventionally, hybrid systems require a backup unit in order to provide power in sensitive situations. In cases when PV panels and battery are not able to supply the required power, DG as backup is used. Equation (2) is used to model the fuel consumption of the DG as follows:

$$FC = A \cdot Y_{DG} + B \cdot P_{DG} \tag{2}$$

Here, Y_{DG} and P_{DG} are output power and nominal power (kW), respectively, A and B are the fuel consumption curve coefficient A = 0.2461 (L/kWh) and B = 0.081451 (L/kWh) [14,37].

2.3. Battery

Batteries are one of the important components used in energy storage and their utilization has been increased since the development of renewable energy technologies. In order to denote the state of charge (SOC) of batteries in charge and discharge conditions Equations (3) and (4) are applied as follows [38]:

$$SOC(t) = SOC(t-1) \cdot (1-\sigma) + \left[E_G(t) - \frac{ED_L(t)}{\eta_{INV}} \right] \eta_{bc} \tag{3}$$

$$SOC(t) = SOC(t-1) \cdot (1-\sigma) - \left[\frac{ED_L(t)}{\eta_{INV}} - E_G(t) \right] \eta_{bf} \tag{4}$$

Based on the abovementioned equations, SOC(t) and SOC(t − 1) refer to the SOC of the battery in times of t and t − 1, respectively. $ED_L(t)$, σ, $E_G(t)$, η_{bc}, η_{bf}, and η_{INV} are energy demand in a specific time (kWh), hourly automatic discharge rate, generated energy (kWh), efficiency of battery bank during charge and discharge (%), and efficiency of inverter (%), respectively [39].

2.4. Inverter

Bidirectional inverters are applied in hybrid energy systems to connect AC and DC bus. Generally, inverters are used to convert DC voltage into AC voltage; moreover, they are used as a rectifier to convert AC voltage of DG to DC voltage that charges the battery.

Technical and economic specifications of different components are provided in Tables 1 and 2.

Table 1. Economical and technical specifications of the system.

Components	Parameters	Value	Refs.
PV system	Panel type	Flat plate	[14,30,40,41]
	Operating temperature (°C)	45	
	Temperature coefficient of power (°C)	−0.41	
	Derating factor (%)	80	
	Capital cost (USD/kW)	735.59	
	Operation and maintenance cost (USD/kW/year)	14	
	Replacement cost (USD/kW)	735.59	
	Lifetime (years)	25	
Battery	Model	EST-Floattech Green Ocra 1050	[40]
	Nominal voltage (v)	52	
	Maximum capacity (Ah)	202	
	Capital cost (USD/kW)	6500	
	Operation and maintenance cost (USD/kW/year)	10	
	Replacement cost (USD/kW)	3500	
Converter	Capital cost (USD/kW)	296.61	[30,40]
	Operation and maintenance cost (USD/kW/year)	14.5	
	Replacement cost (USD/kW)	196.61	
	Efficiency (%)	90	
	Lifetime (years)	15	
Diesel generator	Generator type	Cummins	[5]
	Capital cost (USD/kW)	11,000	
	Replacement cost (USD/kW)	11,000	
	Lifetime (hours)	15,000	

Table 2. Parameter values for the proposed tracker [11].

Component	Lifetime (Years)	Capital Costs (USD/kW)
Horizontal tracker (monthly adjustment)	20	310
Horizontal tracker (continuous adjustment)	20	360
Vertical tracker (continuous adjustment)	20	420
Dual-axis tracking (continuous adjustment)	20	650
PV structure (fixed slop)	20	60

3. Objective Function and Multi-Objective Optimization

3.1. Objective Function (AF)

3.1.1. Net Present Cost

HOMER software is a powerful tool for modeling and design of various hybrid energy systems utilizing renewable energies. The software has fast calculations and acceptable accuracy, which makes it more attractive than other tools in this field. In Figure 3, the procedure of solving problem in HOMER is depicted. Finding the optimal combination of the components by considering the costs of installation, replacement, maintenance and the lifespan of components and determining the economic factors such as cost of energy (COE) and NPC based on the discount and inflation rates are among the most noticeable abilities of the software. Furthermore, by considering different economic and environmental factors, this software will provide useful information on the size and combination of components to supply the power [11]. In this regard, the most significant economic factors determined by the software are NPC and LCOE.

$$\mathrm{AF_1} = \mathrm{Min.(NPC)}$$

$$\mathrm{AF_2} = \mathrm{Min.(LCOE)}$$

Equation (5) is used to determine NPC as follows:

$$\mathrm{NPC} = \frac{\mathrm{Cann}}{\mathrm{CRF(i.n)}} \quad (5)$$

where c_{ann} denotes the total annual cost which is equal to summation of annual replacement, capital, and operation costs of each component. CRF, which is used to convert annual cost to its current value, is determined based on Equation (6). In this study, i and n are interest rate (%) and lifespan (year), respectively, which are considered equal to 10% and 20 years, respectively [42].

$$\mathrm{CRF} = \frac{\mathrm{i}(1+\mathrm{i})^{\mathrm{n}}}{(1+\mathrm{i})^{\mathrm{n}} - 1} \quad (6)$$

In addition, COE, which denotes the mean cost of each kWh of electrical energy generated by the system, is determined by applying Equation (7) [11,43].

$$\mathrm{COE} = \frac{\mathrm{Cann.t}}{\mathrm{Eserved}} \quad (7)$$

where Cann.t is the project total annual cost and Eserved is the generated energy (kWh) in a year. Operation cost is another parameter determined by the software. This parameter refers to the total annual costs and incomes related to the system and is determined by using Equation (8) [11,44].

$$\mathrm{CO} = \mathrm{Cann,t} - \mathrm{Cann,cl} \quad (8)$$

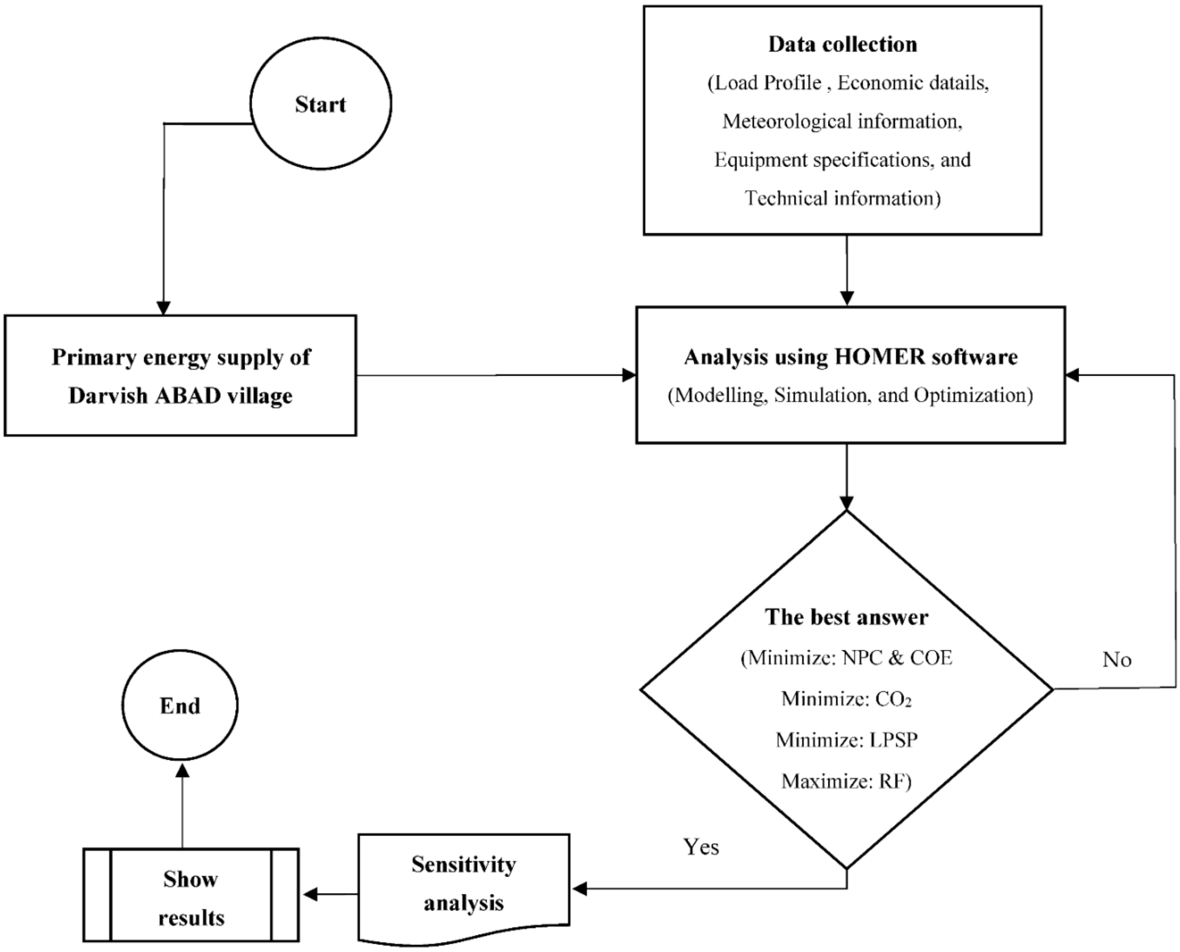

Figure 3. Schematic representation of HOMER software.

3.1.2. Renewable Factor

The aim of this project is minimization of DG output in addition to reduction of NPC and COE, which will lead to decrement in the emission of CO_2 and making the system cleaner. This factor can be assessed by a parameter defined as Renewable Fraction (*RF*).

$$AF_3 = Max.(RF)$$

RF can be estimated by using Equation (9) as follows:

$$RF = \left(1 - \frac{\sum P_{DG}}{\sum P_{PV}}\right) \times 100 \quad (9)$$

where P_{DG} and P_{PV} are the generated power by DG and PV panels, respectively [41,45].

3.1.3. LPSP

The most commonly used approach for reliability is loss of power supply probability (LPSP). In design of hybrid energy systems, the value of LPSP is considered equal to zero which means that 100% of the load is supplied.

$$AF_4 = Min.(\text{LPSP})$$

To determine LPSP, Equation (10) is applied as follows [46]:

$$\text{LPSP} = \frac{\sum_{t=1}^{8760} \text{ED}_\text{L}(t) - \text{E}_\text{G}(t)}{\sum_{t=1}^{8760} \text{ED}_\text{L}(t)} \quad (10)$$

3.1.4. CO_2 Emissions

There are some problems related to the utilization of DG such as environmental pollution. Environmental effects of hybrid systems are assessed based on the emission of carbon dioxide in DG. LCE includes the utilized energy for manufacturing, transfer, and recovery of the DG components and emission of produced carbon dioxide due to the combustion of fuel in DG [11,47], which is determined by using Equation (11).

$$\text{LCE} = \sum_{i=1}^{N} \beta_i \text{E}_\text{L} \quad (11)$$

In Equation (11), β_i $(\text{kg CO2} - \text{eq/kWh})$ and E_L (kWh) are the emission of carbon dioxide in the lifespan of DG and generated or stored energy in battery, respectively.

3.2. Restrictions

The main aim of this study is to decrease carbon dioxide emission, COE, and NPC in addition to ensuring an increase in RF and the reliability of the hybrid system. Decision variables of the study are PV capacity (C_{PV}), DG capacity (C_{DG}), number of batteries ($N_{Battery}$), and inverter capacity ($C_{Inverter}$).

3.2.1. Decision Variables

Adjustment of the decision variables limit is dependent on the problem.

$$\begin{array}{l} 0 \leq C_{PV} \leq C_{PV}^{Max} \\ 0 \leq C_{DG} \leq C_{DG}^{Max} \\ 0 \leq N_{Battery} \leq N_{Battery}^{Max} \\ 0 \leq C_{Inverter} \leq C_{Inverter}^{Max} \end{array} \quad (12)$$

3.2.2. Battery Storage Limitations

Stored energy in the battery is controlled according to the following limits:

$$SOC_{Min} \leq SOC \leq SOC_{Max} \quad (13)$$

where SOC_{Min} and SOC_{Max} are the minimum and maximum storage capacities, respectively.

In Figure 3, schematic of HOMER software is depicted. The aim of this study is to supply the primary energy of a village, Darvish Abad, in South Khorasan, Iran. First of all, it is needed to gather the required information. Afterwards, HOMER software is applied to model, optimize, and simulate the system. The most appropriate option must follow four objective functions. If the best option is in accordance with the defined objectives, sensitivity analysis is performed, else, the initial stages are repeated to reach the best option bases on the defined objective function.

3.3. Operational Strategy

Operational strategy for determining the reliability of the hybrid system in each hour of a year is depicted in Figure 4. The methodology can be summarized as follows:

- If the generated power by the PV panels is higher than the demand, the load is supplied just for the PV panels and the surplus of the generated power is used for charging the battery. If the maximum charge of storage system (SOC_{Max}) is higher than SOC, LPSP will be equal to zero and 100% of the load would be supplied;

- If the demand is higher than the generated power by the PV panels, the battery is discharged and DG starts to work. If the battery becomes fully charged, DG operation will be ceased. If SOC_{Min} is higher than SOC, LPSP must be determined.

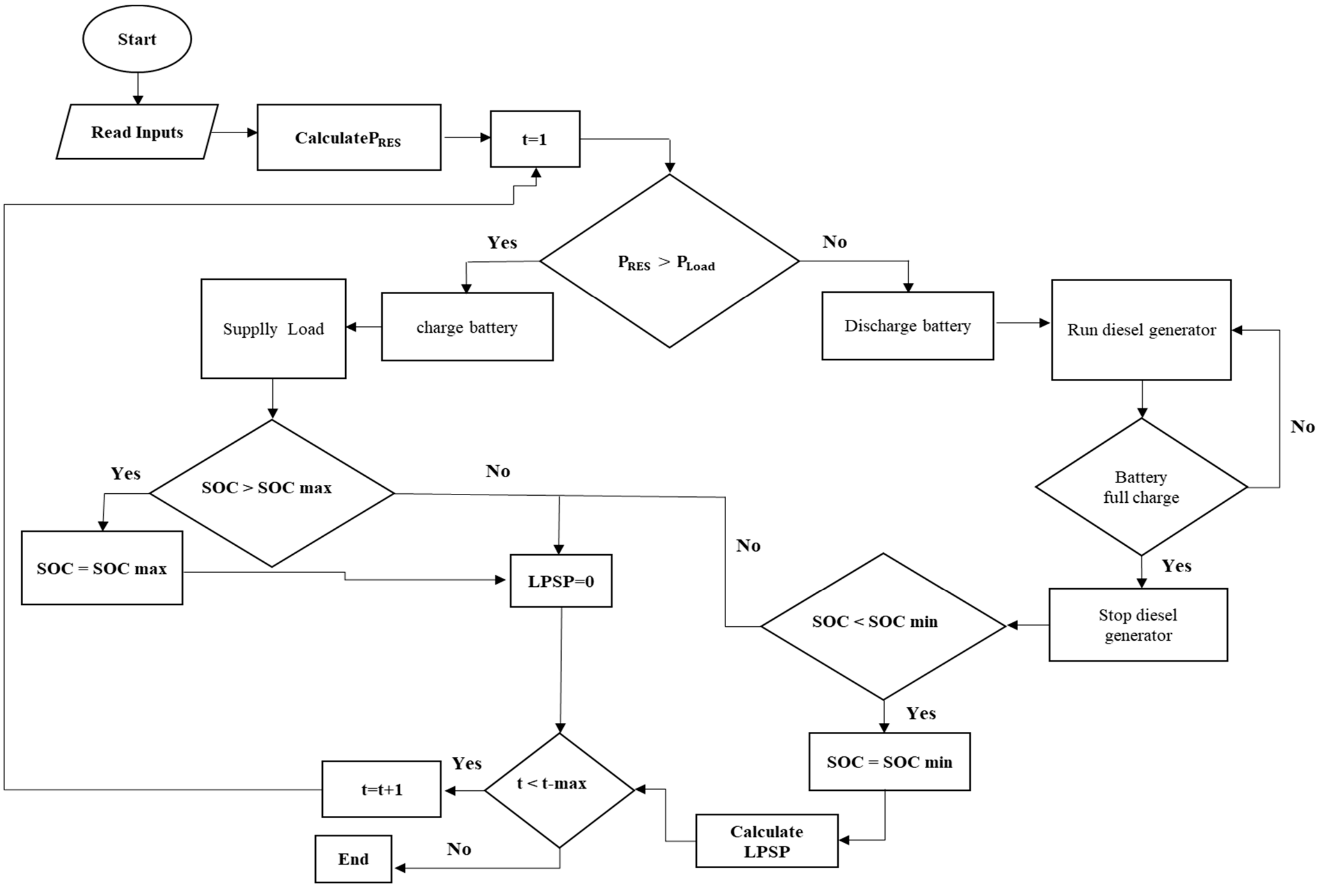

Figure 4. Operating strategy for determination of the system reliability.

4. Results and Discussion

4.1. Case Analysis

This work investigates an off-grid village which is located at 32° and 53 min latitude and longitude of 59° and 13 min. Local electrical energy is supplied by the power plants feed with fossil fuels. In Figure 5, the long-term average of summation of generated power by PV is shown. The electricity demand of ordinary households is depicted in Figure 6, which includes refrigerator, washing machine, TV, vacuum cleaner, lamp, computer, and steam iron. The present case study includes 37 households with average income and four family members, with daily electricity demand of 233.10 kWh and maximum load of 38.38 kWh. In the simulation, peak load is considered in July. As shown in Figure 7, time series data are obtained from HOMER software and the annual load is 85,081.5 kWh.

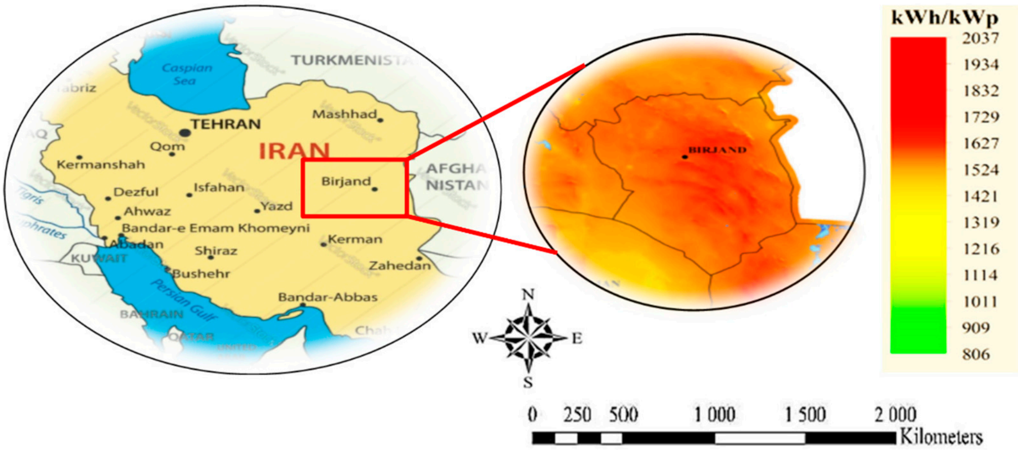

Figure 5. Map of long-term average of annual sum of photovoltaic power production (PVOUT) [48].

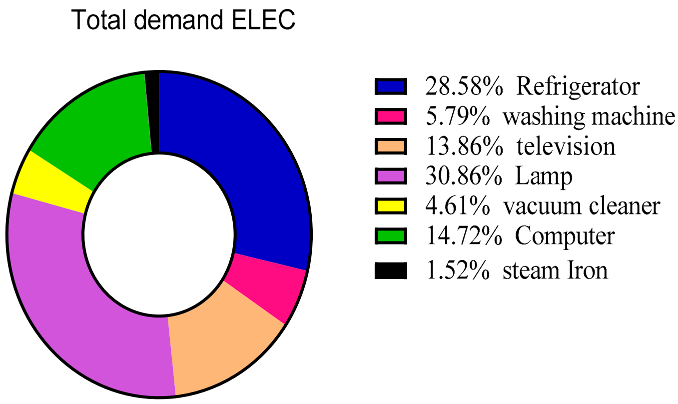

Figure 6. Load demand of ordinary households in rural areas [49].

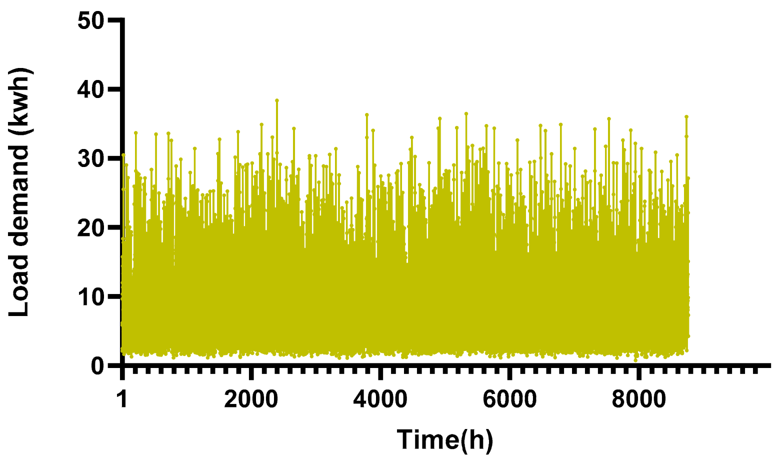

Figure 7. Hourly load demand in a year.

4.2. Meteorological Data

Both solar radiation and PV temperature influence the generated electricity. These factors are defined in HOMER libraries and their impacts on the PV systems output are explained. The following notes provide more details about the utilized data in the current work:

- Solar radiation: solar radiation is in the range of 3.02–7.16 kWh/m^2·day, while the average annual solar radiation for the case study is 5.30 kWh/m^2·day, which is shown in Figure 8. Between April and September, Global Horizontal Irradiance (GHI) is higher than average value and its peak value is in June. Solar radiation in other months, especially November, December, and January, is relatively low [50].

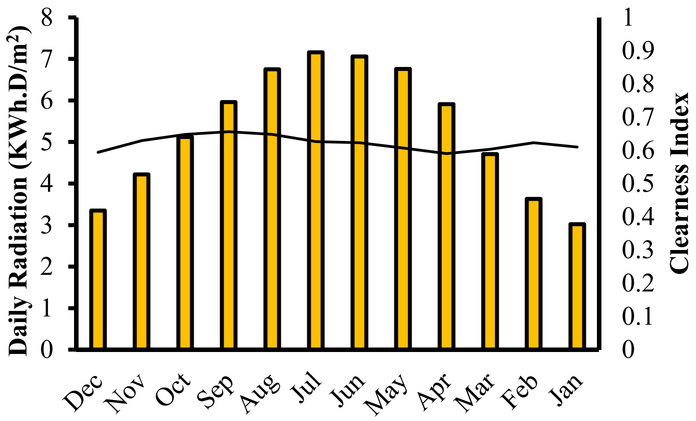

Figure 8. Mean monthly GHI in Darvish Abad village.

- Ambient temperature: the ambient temperature is between 2.9 °C and 23.82 °C, while the annual average ambient temperature for this village is 14.07 °C, as shown in Figure 9. This temperature profile is used to determine the efficiency of the PV since HOMER is able to calculate the output power based on the temperature of the cell [50].

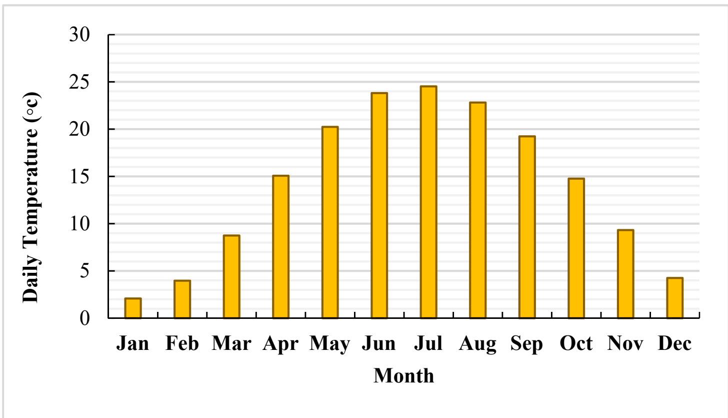

Figure 9. Average daily temperature.

4.3. System Economy and Emission Analysis

In this section, advantages and disadvantages related to the economic and environmental analyses of the five PV systems are discussed. The analysis is based on different factors such as NPC, CO_2 emission, COE, and RF. In Table 3, the optimization results of five PV systems are shown. NPC, COE, and RF are selected as objective functions. According to the results, a hybrid system composed of PV, DG, and battery is the most appropriate choice based on technical and economic criteria. It can be seen that the COE of the hybrid system is between 0.245 USD/kWh and 0.248 USD/kWh. HTCA (Horizontal axis with continuous adjustment) and VTCA (Vertical axis with continuous adjustment) have the highest and the lowest NPC, respectively, since DG provides lower energy compared with HTCA and has the lowest costs related to PV.

Table 3. The optimization schemes and results of five PV technologies.

Tracker	WTC	HTMA	HTCA	VTCA	DTCA
NPC (USD)	548,600	548,626	549,139	548,085	548,597
COE (USD/kwh)	0.247	0.247	0.248	0.245	0.247
Number of batteries	15	12	14	15	17
Bidirectional inverter (KW)	33.8	33.8	33.8	33.8	33.8
Number of DG	1	1	1	1	1
DG power (kW)	30	30	30	30	30
PV cells (kw)	680	675	670	664	663
Annual PV cost (USD)	426,964.3	427,182.3	427,692.3	427,192.3	427,742.3
Annual battery cost (USD)	132,088.1	130,300.1	131,088.1	132,088.1	133,108.1
Annual inverter cost (USD)	44,222.88	44,222.88	44,193.77	44,222.88	44,193.77
Annual DG cost (USD)	55,668.93	55,675.93	55,127.45	56,210.42	55,668.93
PV energy (kwh/yr)	1,143,329	1,204,164	1,235,558	1,420,944	1,528,611
DG energy (kwh/yr)	1279	1270	1289	1243	1271
Fuel cost (USD/yr)	57	67	207	179	57.9
Renewable fraction (%)	98.3	98.5	98.4	98.5	98.5
CO_2 emissions (kg/yr)	373	385	400	345	373
DG running time (h)	27	27	29	25	27

Since this study focused on the hybrid systems based on PV and DG, the results indicate the HTCA has the highest COE and NPC. Most of the required power of this system is provided by PV panels and due to their higher costs compared with battery, DG, and inverter, the system's overall cost increases. In addition, the fuel cost of this system must be considered which shows that HTCA has the highest fuel cost, 207 USD/yr.

HTCA is composed of a DG with 30 kW capacity and 14 batteries. The operating hours of DG are 29, which causes CO_2 emission of 400 kg in a year. The results of the simulation reveal that this system has the highest emission among the considered technologies due to the fossil fuel consumption and its operating hours. Reduction in the emission of pollutants requires a decrease in operating hours of DG. The energy generated by the DG in cases of HTMA, DTCA (Two-axis with continuous adjustment), WTC (No tracking) and HTCA is 2.17%, 2.25%, 2.89%, and 3.7% higher than VTCA. According to the results, the number and capacity of DG are 1 and 30 kW, respectively, and are constant for all of the systems.

DTCA has the lowest NPC after VTCA which is due to lower fuel cost and operation hour of DG. In addition, its COE is decreased compared with HTCA and the number of batteries is increased which make it possible to store more energy. The NPC of WTC is more than DTCA; however, the COE of both of them is equal. It has the highest PV capacity and as a result, the annual cost of PV is less than the other four methods. HTMA has more NPC and COE than the previous three methods because the cost of fuel is reduced but it is still not the most ideal option.

Since the aim of the study is finding a system with minimum NPC and COE, results show that VTCA is the best option. In addition, with 98.5% of RF, it is the cleanest technology for off-grid power generation. Annual emission of this system is 1867 kg, which is lower than other systems, due to the reduction in operation hours of DG and fuel consumption.

According to Figure 10, VTCA and HTCA have the minimum and maximum NPC, respectively. According to this figure, NPC of the hybrid systems with WTC, HTMA, HTCA, and DTCA are 0.076, 0.075, 0.12, and 0.095% higher than the system with VTCA. In all of the systems, PV has the highest contribution in the cost which is followed by battery, fuel, and inverter, respectively.

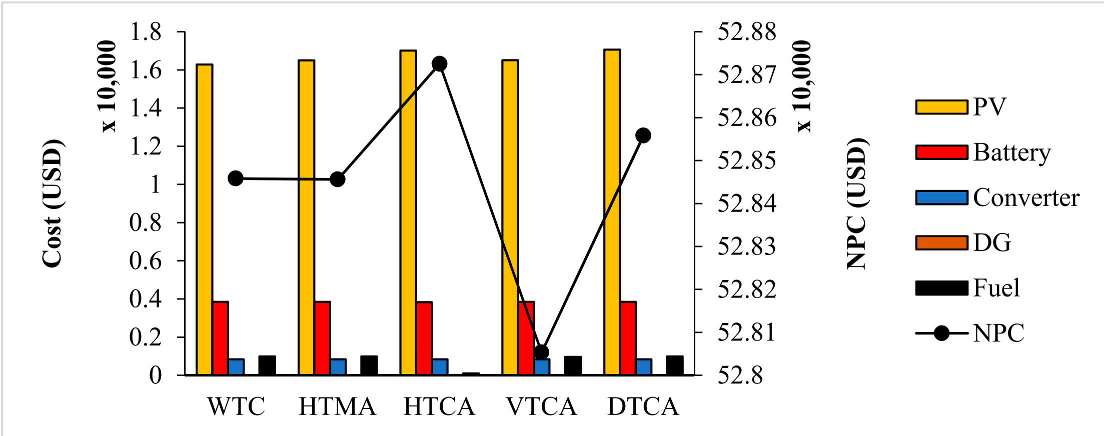

Figure 10. NPC and the cost of a combined system of 5 technologies.

In Figure 11, emission of carbon dioxide and COE related to the investigated systems are shown. It shows that HTCA has the highest emission, mainly due to the DG operation hours, while the minimum emission belongs to VTCA. COE of the systems with WTC, HTMA, HTCA, and DTCA are 0.81%, 0.4%, 1.22%, and 0.81% higher than VTCA, respectively.

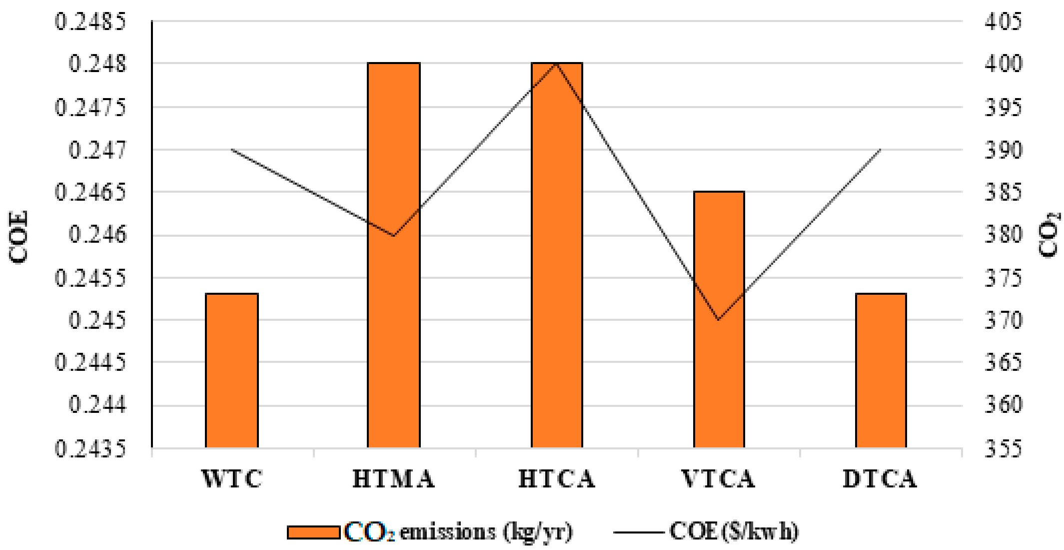

Figure 11. CO_2 and COE emissions related to the five technologies of hybrid systems.

Figure 12 illustrates the rankings of the investigated systems. According to this figure and the considered factors, the system with VTCA outperforms the others.

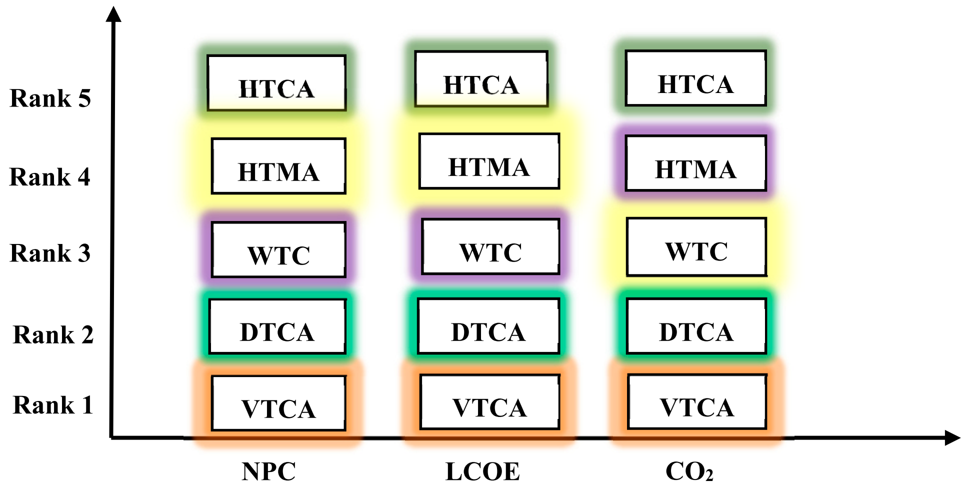

Figure 12. Comparison of the advantages and disadvantages of hybrid systems.

4.4. Sensitivity Analysis

In the final section, sensitivity analysis of the system with VTCA input parameters with high influence on the NPC is performed. Sensitivity of NPC on the interest rate, PV cost, battery cost, fuel cost, DG cost, and inverter cost is analyzed. According to Figure 13, 20% reduction in interest rate and 40% in PV cost causes 0.014% increment in NPC compared with initial condition. Depending on the shape, the NPC increases by 36% as the interest rate decreases. As a result, the working hours of diesel generators have increased, which has increased CO_2 emissions, as well as the amount of energy produced by diesel generators and PV. Yet with the decline in PV costs, NPC have fallen by 36%. The amount of carbon dioxide emissions, the amount of energy produced by PV and the DG have increased and decreased according to the initial condition, respectively. However, the cost of fuel has decreased by 69% compared to the initial situation. As you can see, NPC is affected by the cost of PV.

In Figure 14, it is shown that fuel and battery cost have significant effect on NPC. A 20% reduction in costs of battery is noted and fuel reduces NPC by 5%. By increasing the cost of diesel generator fuel, the fuel consumption of this system can be reduced because it hinders the cost effectiveness of diesel generator energy and the economic feasibility of the system. In this regard, utilization of DG in off-grid remote region is not cost effective by increase in fuel cost. Finally, load demand is estimated by PV systems. A 20% decrease in battery cost causes a 3.3% decrease in NPC. Results indicate that CO_2 emission and generated power by DG compared with the initial condition are increased and decreased, respectively. In addition, the cost of fuel is decreased by 66%.

According to Figure 15, diesel generator cost and inverter cost are sensitive to NPC. By changing the cost of diesel generator and inverter cost, NPC is reduced by 2%. The results show that increasing and decreasing the inverter cost is directly related to NPC. According to the figure, the NPC decreases by 0.5% as the inverter cost decreases.

From the sensitivity analysis performed, we conclude that the greatest impact on NPC is the cost of fuel and batteries, and this change increases linearly with increasing NPC costs and decreases with decreasing NPC costs.

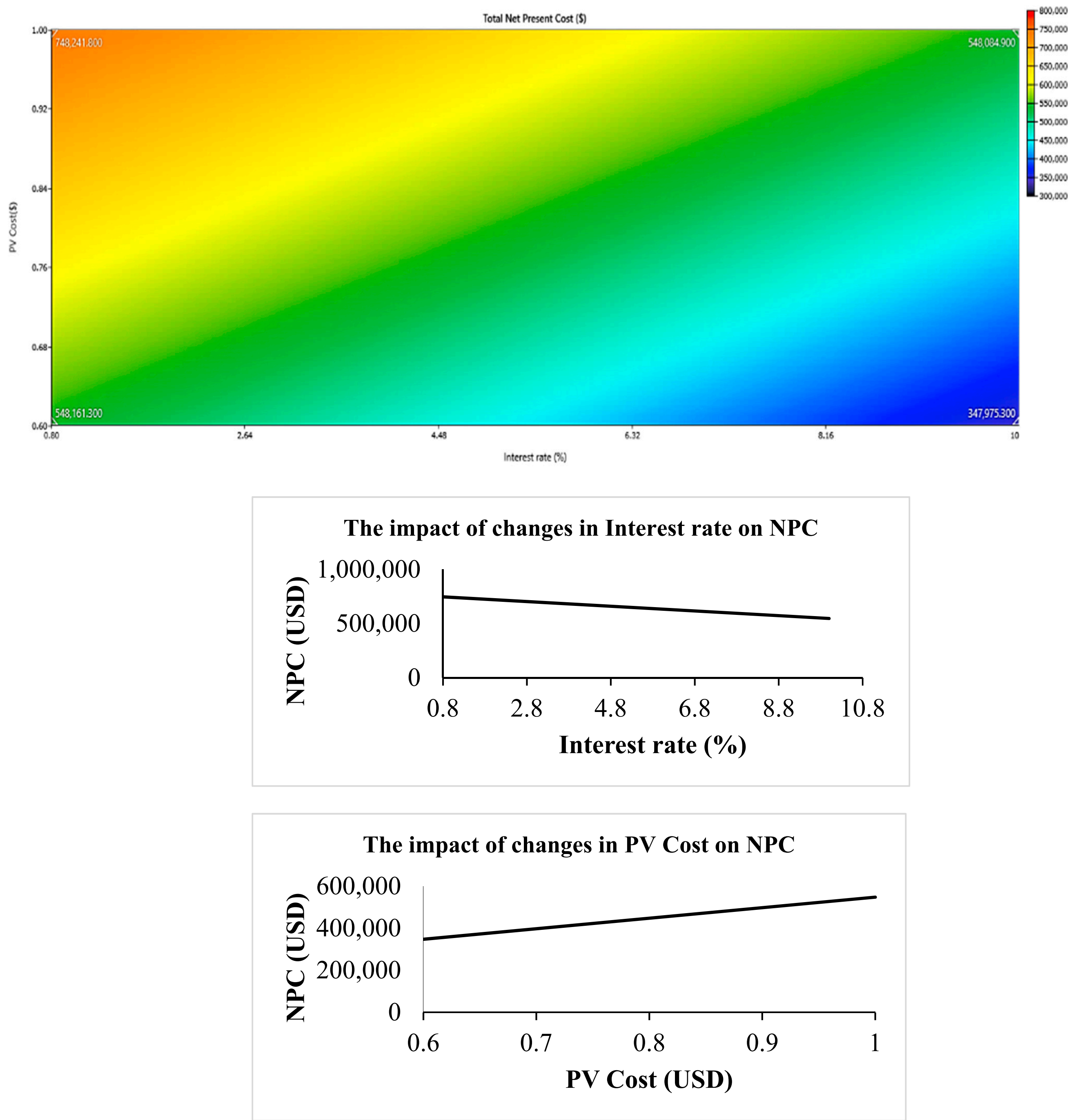

Figure 13. The sensitivity results of the hybrid system with VTCA: PV costs and interest rates.

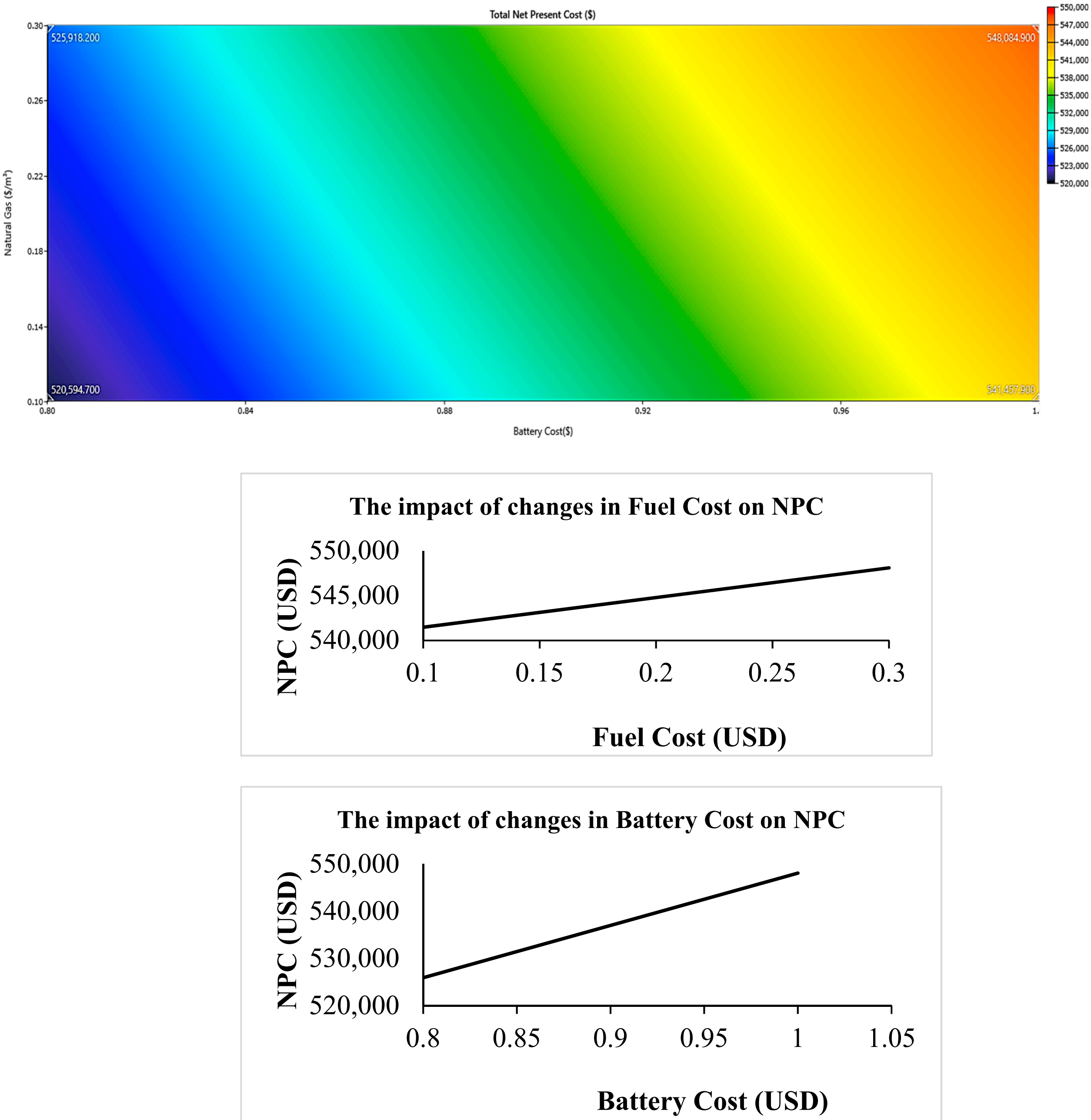

Figure 14. The sensitivity results of the hybrid system with VTCA: Battery costs and Fuel costs.

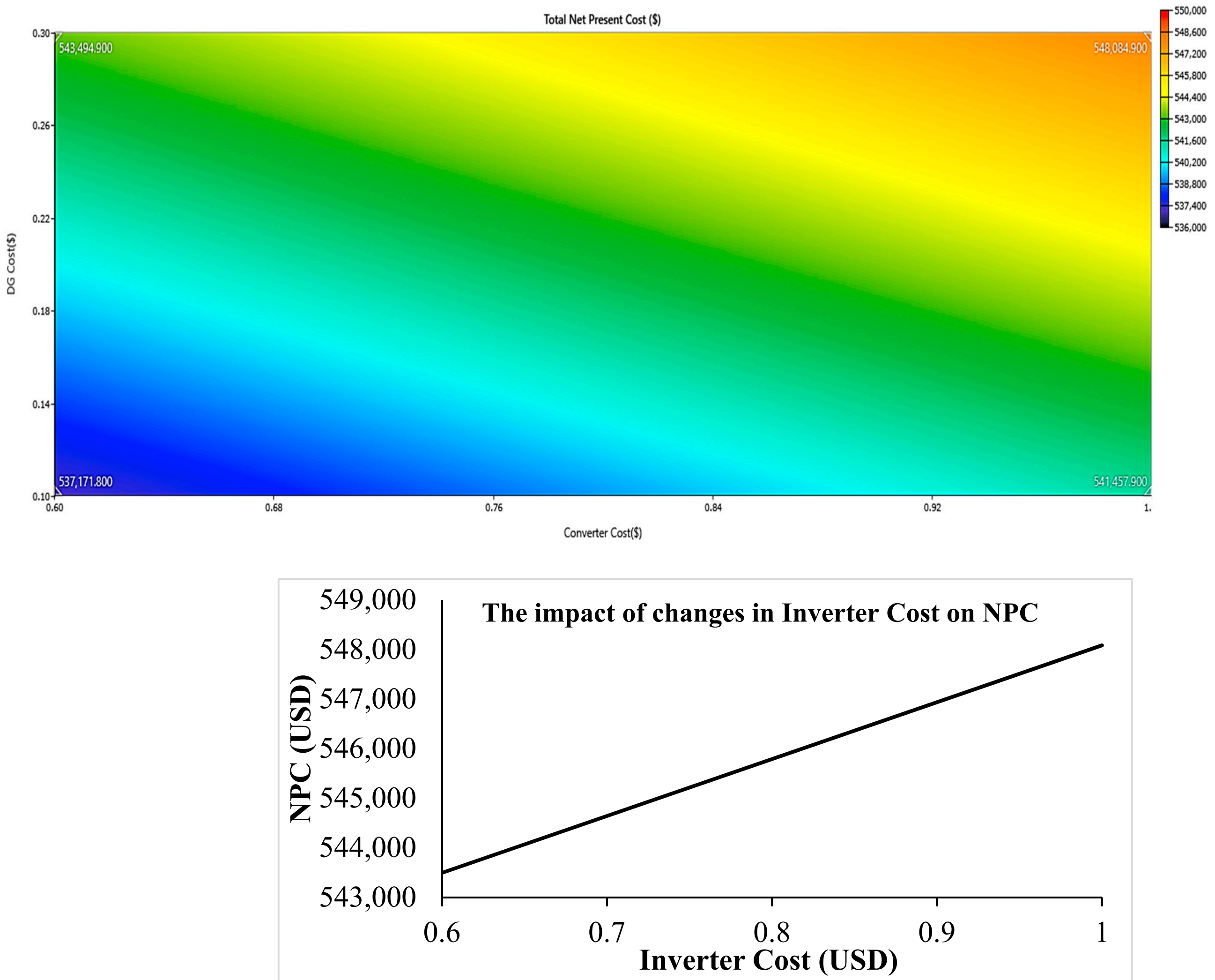

Figure 15. The sensitivity results of the hybrid system with VTCA: Inverter costs and Fuel cost.

5. Conclusions

In this work, different tracking systems are applied in a hybrid system composed of PV, DG, battery, and inverter for a village, Darvish Abad, in South Khorasan, Iran. The aim of the study is a reduction of NPC and COE and an increase in RF and reliability. According to the results, the hybrid system with VTCA is the most appropriate option from economic and technical points of view. In addition, sensitivity analysis is performed on the hybrid system with VTCA and effects of interest rate and costs of PV, battery, fuel, DG, and inverter are assessed. The main findings can be summarized as follows:

- The hybrid system with VTCA has the lowest NPC, while the ones with HTCA has the highest value of NPC. NPC of the systems with WTC, HTMA, HTCA, and DTCA are 0.076%, 0.075%, 0.12%, and 0.095% higher than the system with VTCA. The hybrid system with VTCA has the lowest emission;
- A 20% reduction in interest rate and a 40% decrease in PV cost causes a 0.014% increase in NPC compared with the initial condition. As the interest rate decreases, the NPC increases by 36%. However, with the reduction in the cost of PV, the NPC has decreased by 36%, according to the NPC results, which is affected by the cost of PV;
- A 20% reduction in battery and fuel cost causes a 5% decrease in NPC. The results indicate that NPC is affected by fuel cost and increase in it cause reduction in utilization of DG and increment in use of PV. In addition, it is found that a 20% decrease in battery cost leads to 3.3% decrement in NPC;

- Decrease in NPC value is 0.5% proportional to the reduction in inverter cost.

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Nomenclature

A	Fuel consumption curve coefficient (L/kWh)
AC	Alternative current
B	Fuel consumption curve coefficient (L/kWh)
β_i	Emission of carbon dioxide in the lifespan of DG
C_{PV}	PV capacity
C_{DG}	DG capacity
$C_{Inverter}$	Inverter capacity
CO	Operation cost
Cann.t	Project total annual cost
Cann,cl	Incomes related to the system
CRF	Convert annual cost to its current value
Cann	Total annual cos
DG	Diesel generator
DC	Direct current
E_G	Generated energy (kWh)
ED_L	Energy demand in a specific time (kWh)
Eserved	Generated energy (kWh) in a year
E_L	Generated or stored energy in battery (kWh)
FC	Fuel consumption of the DG
F_{PV}	PV derating factor (%)
GHI	Global Horizontal Irradiance
G_T	Solar radiation (kW/m^2)
$G_{T,STC}$	Standard solar radiation (kW/m^2)
HOMER	hybrid optimization of multiple energy resources
HTMA	Horizontal Axis with Monthly Adjustment
HTCA	Horizontal Axis with Continuous Adjustment
i	Interest rate (%)
LCOE	Levelized cost of energy (USD/kwh)
LPSP	Loss of power supply probability
LCE	Internal combustion engine
NPC	Net present cost (USD)
n	lifespan (year)
$N_{Battery}$	Number of batteries
PV	Photovoltaic
P_{PV}	Power by each PV panel
P_{DG}	Nominal power (kW)
RF	Renewable fraction (%)
R_{PV}	Rated capacity (kW)
SOC(t)	SOC of the battery in times of t
$SOC(t-1)$	SOC of the battery in times of t-1
DTCA	Two Axis with continuous Adjustment
TV	Television
VTCA	Vertical Axis with Continuous Adjustment
WTC	No tracking
Y_{DG}	Output power (KW)
η_{INV}	Efficiency of inverter (%)
η_{bc}	Efficiency of battery bank during charge (%)
η_{bf}	Efficiency of battery bank during discharge (%)
σ	Hourly automatic discharge rate

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