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Research Article

Design and Simulation of a PV System Operating in Grid-Connected and Stand-Alone Modes for Areas of Daily Grid Blackouts

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The electricity in Gaza, Palestine, is limited and scheduled for 4-10 hours per day due to political reasons. This status represents a real problem for different sectors. This paper presents an effective solution especially for the energy supply problem in the residential sector by using an unconventional PV system which operates in stand-alone and grid-connected modes. The system includes a storage battery block with a proper capacity to secure for continuous power supply of a residential house with a daily energy load of 10 kWh. It was found that an unconventional PV system of 3.2 kWp and a storage battery block of 19.2 kWh will be able to cover the total daily energy demands of the house including the outlined electricity cutoff hours. The design of this system and specifics of its components are presented in this paper. The system was simulated by Matlab software, where the daily load curve, grid cutoff hours, and the monthly solar radiation are considered. The obtained simulation results show that the produced PV energy exceeds the load demands during nine months of the year, and thereby, a high battery state of charge (SOC) in the range of 73-84% is achieved. During the three months of the lowest solar radiation (Dec.-Feb.), the produced PV energy is equal to the load demand while the battery state of charge varies in the range of 40-49% which verifies the appropriateness of the proposed PV system. The daily energy yield of the PV system varies between 2.6 and 5.4 kWh/kWp in January and July, respectively, which corresponds to a performance ratio of 90% and 66.25%, respectively.

1. Background and Problem Statement

In Palestine, most of the electrical energy is purchased and controlled from Israeli Electric Company (IEC) [1]. Electrical power is transmitted and supplied through connection points with specified and quoted capacities. In some cases, especially in Gaza, the electrical demand is more than the supply limit; this obliges the distribution companies to schedule the power supply over different periods varying from four to ten hours a day [2, 3]. This status represents a real problem for residents and all other sectors. This problem is available since over ten years, and no indications for its end during the next years are available due to the continuous unchanged political situation. However, installing PV systems on residential houses and other private or common utilities with relatively low daily energy consumption represents an effective solution for a wide range of such consumers which represents a considerable part of the total electric power consumption in Gaza. The PV power system can provide a continuous power supply during the grid blackouts, and it can inject the excess produced power in the electrical grid during the day periods. However, grid-connected PV systems cannot continue supplying electrical power during grid blackout hours due to the islanding mode of the inverter which is an essential main feature for each grid-connected inverter to satisfy the safety issues. Therefore, the electrical power generated from the PV system during blackout hours will be lost if no storage battery is available in the PV system. This leads to a considerable energy loss and will result in increasing the payback period of the PV systems. The aim of this paper is to present a solution for such a problem by introducing an unconventional PV system which includes storage batteries, charge

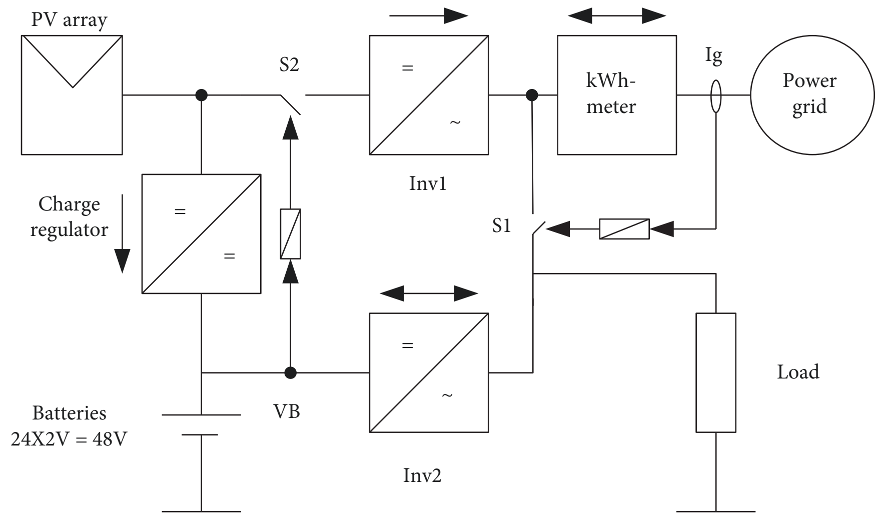

Figure 1: Schematic diagram of the proposed PV backup system.

regulator, grid-connected inverter, bidirectional AC/DC converter, and control system to secure for continuous power supply. This system is designed to enable exploiting fully the hours of grid availability not only in supplying the load but also in charging the battery. On the other hand, it will exploit fully the PV-generated power in charging the battery, supplying the load and injecting the excess energy in the grid. The novelty of the proposed PV system, in comparison with other conventional PV systems, is that it can operate in stand-alone and grid-connected modes without reducing the safety measures required for the islanding mode. The proposed system has been until now not built in Palestine, and publications on such a system were not found due to its particularity in operating in stand-alone and grid-connected modes in a city of timewise irregular daily grid interruptions for several hours. On the other hand, unlike the conventional grid-connected PV systems, which operate mostly at a DC voltage in the range of 400-600 V, the proposed system operates at much lower DC voltage amounting to 48 V which is safer and facilitate reducing the number of necessary battery cells to only 24 cells.

The proposed PV system has been simulated by Matlab software. The obtained simulation results, presented in this paper, verify the appropriateness of the developed system design and show that the produced and stored electrical energy is fully enough to cover the total load demands along the year, which means a suitable solution for solving the grid blackout problem for a large portion of the residential sector in Gaza. Unfortunately, the obtained testing results could not be compared with other equivalent results due to lack of publications on such an unconventional PV system which is designed for a particular case. The description of the proposed PV system and its components are discussed in Section 2. The design and sizing of the system components are presented in Section 3. Finally, Section 4 presents the modeling and simulation of the system and discusses the obtained testing results.

2. Description of the Proposed PV System

The proposed PV system can operate in both modes of operation, grid-connected and stand-alone. The system block diagram is illustrated in Figure 1. It mainly includes the PV generator, block batteries, power conditioning units, and control system.

PV Generator. It consists of PV modules connected in series and parallel depending on the selected DC system voltage and power. The PV modules are selected to be monocrystalline or polycrystalline silicon because of their high efficiency and less degradation over the life time periods in comparison with other PV technologies.

Storage Block Batteries. The battery block consists of stationary cells that can stand very deep discharge and have a high cycling rate exceeding 1000 times due to frequent grid blackouts. These battery cells have a high ampere hour efficiency in the range of 80-90% and have long life time exceeding 10 years [4, 5].

Battery Charge Regulator. It is used to regulate the charging process of the battery block and to protect it against deep discharge and extreme overcharge. It will be connected within the system as shown in Figure 1; the voltage sensor will measure the battery voltage and close or open switch S2 according to battery state of charge.

Inverter-1. It is a grid-connected inverter to convert DC input power of PV generators to AC power injected into the grid. It includes control algorithms for maximum point tracking (MPPT), synchronization to make the inverter leaded by the grid, and anti-islanding algorithm to secure for safety during grid cutoff times.

Inverter-2. It is a bidirectional power converter with ability to act as an inverter, converting DC to AC power, and as a rectifier to convert AC power to DC power. In the first mode, it will provide the load with AC power from the battery block during the grid outage hours. In the second mode, it acts as a rectifier to charge the battery block from the grid during its active hours. This inverter is not designed to supply the grid with AC power from the battery block. The current sensor (Ig) is mainly used to disconnect inverter-2 in case of grid blackout.

Bidirectional kWh Energy Meter. This meter is used to count the power consumed from the grid while supplying the load or charging the battery block when required and to count the power injected into the grid from the PV system. This meter is installed on the basis of the electricity regulation used in Palestine called net metering regulation.

3. Design and Sizing the PV System

Sizing the proposed PV system components shown in Figure 1 will consider the following stated parameters:

(i) Annual average solar energy intensity on horizontal surfaces in Palestine is 5.4 kWh/m^2 day, which corresponds to average peak sunshine hours (PSH) = 5.4 h/day [6]

(ii) The daily average energy consumption of a residential house or one public or private utility in Gaza City amounts to 10 kWh/day; such an amount of energy represents in average the consumption of a considerable percentage of residential houses and small private or public foundations in Gaza. In addition, the necessary mounting area of the corresponding PV generator amounts to about 25 m^2 which facilitates its installation on a house rooftop

(iii) The efficiency (η_{inv}) of inverter-1 and inverter-2 amounts to 93%, while the η_{CR} is 95% for the charge regulator

(iv) Ampere hour efficiency of the block battery is $\eta_{\text{BAh}} = 85\%$

(v) The DC system voltage is chosen to be 48 V in order to limit the battery block voltage under a dangerous value

3.1. PV Generator Sizing. The PV array peak power P_{PV} is obtained as follows [7]:

$$P_{\text{PV}} = \frac{E_{\text{d}}}{\text{PSH} \times \eta_{\text{CR}} \times \eta_{\text{inv}}}, \quad (1)$$

where E_{d} is daily energy consumption of the residential house (kWh/day), PSH is peak sunshine hours (hours/day), η_{CR} is charge regulator efficiency, and η_{inv} is inverter efficiency.

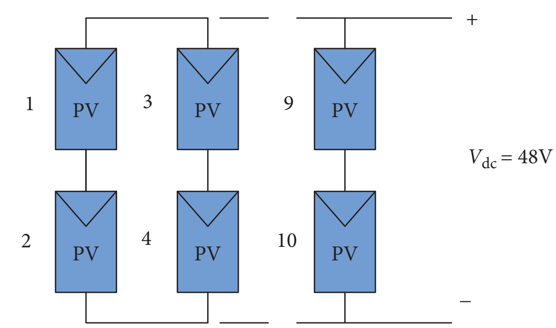

Figure 2: The PV generator rated at 3200 Wp/48 V.

Considering the outlined parameter values, we obtain the peak power of the PV generator in Watt peak (Wp):

$$P_{\text{PV}} = \frac{10,000}{5.4 \times 0.95 \times 0.93} = 2096\ \text{Wp}. \quad (2)$$

A PV generator with a peak power of 3200 Wp will be selected to secure for continuous power availability during grid outage hours and to compensate for cloudy days and all system electrical losses. In addition, increasing the PV peak power will secure for maintaining an appropriate level of state of charge of the battery block. A poly- or monocrystalline PV module with 72 cells connected in series and a peak power of 320 Wp will be used. In this case, 5 parallel strings, each consists of 2 PV modules connected in series, will constitute the PV generator which has a nominal DC voltage of 48 V as shown in Figure 2. This voltage is selected to match with the nominal voltage of the storage battery block.

3.2. Design of the Storage Battery Block. The nominal battery block voltage is selected to be 48 V, which is safe when installing the battery block in a residential house.

The battery block storage capacity will be selected to cover the energy load demands for two days without the sun and electric grid. The total ampere-hour C_{BAh} is obtained as follows [7]:

$$C_{\text{BAh}} = \frac{E_{\text{db}} \times \text{AD}}{\text{DOD} \times \eta_{\text{BAh}} \times V_B}, \quad (3)$$

where E_{db} is the daily energy required from the battery ($E_{\text{d}}/\eta_{\text{inv}}$), DOD is the permissible depth of discharge, AD is autonomy days, η_{BAh} is the ampere hour efficiency of the battery cell, and V_B is the selected nominal DC voltage of the battery block.

Considering realistic values for these parameters represented in AD = 2.25 days, DOD = 0.8, and $\eta_{\text{BAh}} = 0.85$, as well as $V_B = 48$ V, the ampere hour capacity is obtained as

$$C_{\text{Ah}} = \frac{(1000/0.93) \times 2.25}{0.8 \times 0.85 \times 48} = 741.2\ \text{Ah}. \quad (4)$$

In order to increase the battery storage safety factor and to respect the industry produced norm values, a lead acid block battery cell rated at 800 Ah/2 V will be selected to

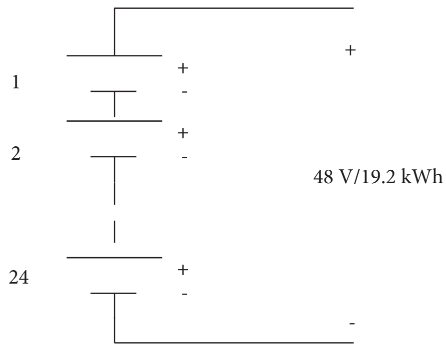

Figure 3: The storage battery block rated at 48 V/800 Ah-19.2 kWh.

constitute the storage system which consists of 24 cells connected in series to present a DC power source of 48 V/800 Ah as shown in Figure 3. The energy storage capacity of this battery block is $C_{wh} = 19.2$ kWh, which is size-wise appropriate for indoor installation in a residential house.

3.3. Selecting the Charge Regulator. Respecting the open circuit voltage of the PV generator and its peak power, the charge regulator will be rated at an input voltage in the range of 44-86 V and a rated power of 3.2 kW while its nominal output voltage is 48 V.

3.4. Selecting the Inverter (Inv1). Inverter-1 is a single-phase DC/AC inverter rated at 4 kVA with an output voltage and frequency amounting to 220 V and 50 Hz, respectively, and operates at a unity power factor. It supplies the load directly via switch S1 and the electric grid with power produced by the PV generator via bidirectional kWh-meter as shown in Figure 1. This inverter is leaded by the grid, and it is designed to shut off at the instant of grid blackout to secure for fully safety.

3.5. Selecting the Bidirectional Converter (Inv2). This is a bidirectional converter rated at 5 kVA which is selected to be appropriate for supplying the load with AC power from the battery block and charging the battery from the grid when the PV power is limited for a long period as in the winter season.

3.6. The Operating Modes of the System. Different conditions will lead the system to operate in different modes; these conditions include the solar radiation level, grid interruption times, battery state of charge, and the load demand. At any of these conditions, the system in Figure 1 will choose to work at the appropriate mode according to Table 1.

4. Evaluation of System Performance by Simulation

The system simulation is performed by considering the system design described in Section 3. In this approach, the PV system plus the energy stored in the battery block are used to cover the load demand when the grid is not available. During the hours of grid availability, its power will be used to cover the load demand and to charge the battery block depending on its state of charge. For each hour step, the simulation software compares the energy demand and the PV energy generated, and according to the difference, a decision to charge/discharge the battery or inject excess power to the grid will be made.

4.1. Typical Daily Load Curve Used in Simulation. The daily load profile reflects the load variation which depends on the behavior of consumers. For a common residential house in Gaza, the main loads are lighting, TV, computer, and domestic appliances such as refrigerators, freezer, and washing machines. The load profile shown in Figure 4 is considered in the simulation software.

Based on the daily load curve shown in Figure 4, the annual production of the PV power system, the battery state of charge, and the energy balance have been investigated by software simulation.

4.2. Mathematical Modeling of System Components. The purpose of system simulation is to check the system performance at different conditions and times of the year. It is performed by using mathematical models of the PV array, batteries, charge regulator, and inverters. The input data are hourly data of solar radiation, ambient temperature, and daily load curve. A brief description of the mathematical models is represented in the following equations.

PV Output Power Estimation. DC power generated from the PV system is mainly dependent on different factors, including PV peak power at standard test condition (STC), solar radiation, and cell temperature. Such a simple model is represented in [8, 9]:

$$P_{\mathrm{PVout}} = P_{\mathrm{PVpeak}} \times \left(\frac{G}{G_{\mathrm{ref}}}\right) \times \left[1 + K_T\left(T_c - T_{\mathrm{ref}}\right)\right], \quad (5)$$

where P_{PVout} is the output power of the PV array, P_{PVpeak} is the power of the PV array at STC, G is solar radiation in W/m^2, G_{ref} is solar radiation at STC amounting to 1000 W/m^2, K_T is the temperature coefficient of mono- and polycrystalline Si cells amounting to $(K_T = -3.7 \times 10^{-3}(1/^{\circ}C))$, T_{ref} is the reference temperature at STC amounting to 25°C, and T_C is the cell temperature calculated by the following empirical equation [10]:

$$T_C = T_{\mathrm{amb}} + (0.0256 \times G), \quad (6)$$

where T_{amb} is the ambient temperature.

Storage Block Batteries. Batteries are used to store the excess power generated by PV in case of grid blackout or when the system operates in the stand-alone mode. Also, they support the load when the PV power is less than the load demand. The equations used for representing the energy of charging and discharging the battery block (E_B) are as follows.

The battery block works in two different modes known as charging and discharging. During the charging mode (equation 7), the PV power multiplied by the efficiency of the

Table 1: Operating modes of the system.

Mode #	S1	S2	Description
1	0	0	Grid cutoff, battery charging from the PV generator, load is supplied with power from the battery block.
2	1	0	Grid available, load supplied directly from the grid. Battery state of charge is low, the battery block is charged at the same time from the PV generator and the grid.
3	0	1	Grid available, battery charging from a PV generator and excess produced power injected into the grid and supplies the load.
4	1	1	This state is not suitable to be used in this system (not allowed).

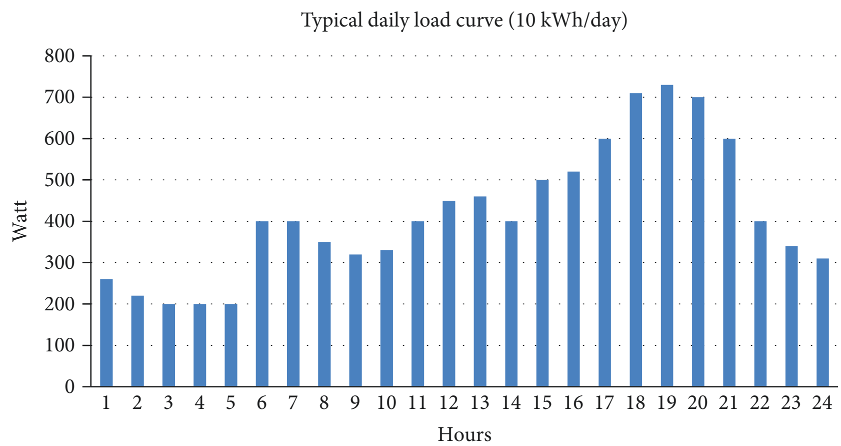

Figure 4: Typical daily load curve of a residential house in Gaza used in the simulation process.

charge regulator exceeds the input power of the bidirectional inverter (inv2) which equals to the load power divided by the efficiency of inverter-2. This power (P_{ch}) multiplied by charging efficiency of the battery then by one hour will be added to the energy of the battery (equation 8). Multiplication is by one hour because the simulation period is equal to one hour.

During the discharging mode (equation 9), the battery will discharge power (P_{disch}) to cover the deficit occurring when the load exceeds the PV power. The power discharged from the battery represents the PV power multiplied by the charge regulator efficiency subtracted from the load power divided by the efficiency of the bidirectional inverter (inv2), then all divided by battery charging efficiency as shown in (9). The discharge power will be multiplied by one hour, then subtracted from the energy of the battery block (equation 10):

(a) Charging mode

$$P_{ch} = [(P_{PVO} \times \eta_{CR}) - (P_L/\eta_{inv})] \times \eta_{BAh}, \quad (7)$$

$$E_B(t) = E_B(t-1) + (P_{ch} \times 1\text{ hour}), \quad (8)$$

(b) Discharging mode

$$P_{disch} = [(P_L/\eta_{inv}) - (P_{PVO} \times \eta_{CR})]/\eta_{BAh}, \quad (9)$$

$$E_B(t) = E_B(t-1) - (P_{disch} \times 1\text{ hour}), \quad (10)$$

where E_B is the electrical energy available in the battery (Wh), P_{PVO} is the output power of the PV array (W), P_L is the required load power (W), P_{ch} is the power charged to the battery during the charging mode (W), and P_{disch} is the power discharged from the battery during the discharging mode (W).

4.3. Flow Chart Used for System Simulation. Different cases were considered to develop the appropriate simulation software:

First Case. Sufficient energy is being generated by the PV system. Covering the load demand by PV energy will have the priority over discharging the battery or using the grid if it is available. Excess PV power if available will be injected into the grid or charging the battery block according to its SOC.

Second Case. The generated PV power is not sufficient to supply the load. The priority here is to use the grid power if it is available; if grid is not available, then discharge the required load energy from the battery block.

Third Case. The PV power generated is not sufficient to cover the load demand and the battery SOC is low. Then the grid is

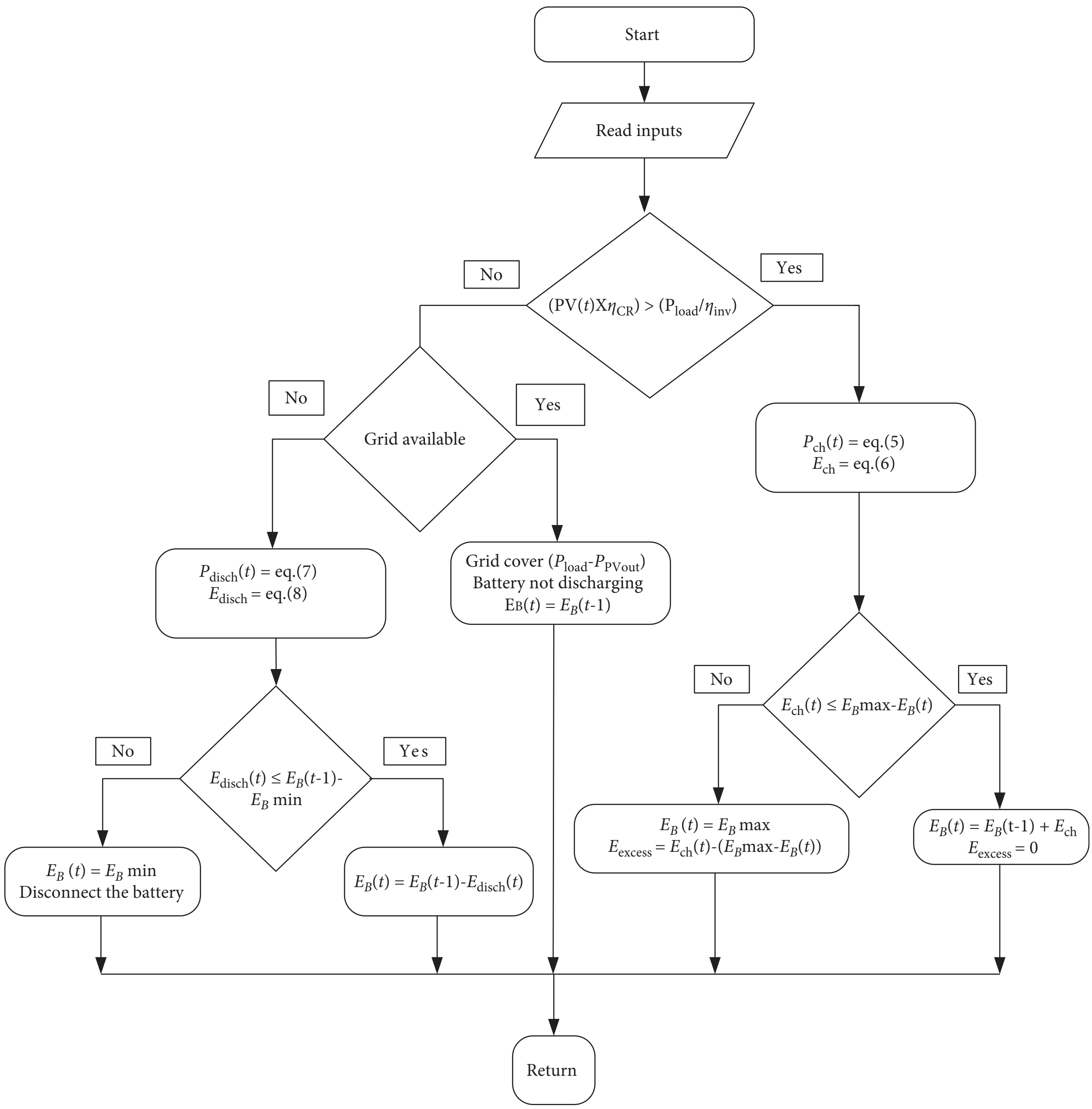

Figure 5: Flow chart used for system simulation.

used to charge the battery block and to cover the load demand at the same time.

It is a matter of fact that the grid interruption periods are time wise irregular, depending on the situation of electricity and not be chosen by the PV user. Hence, the simulation considers the PV system as a stand-alone one which is the worst case. Accordingly, a software program basing on the flow chart illustrated in Figure 5 was developed for evaluation of the system performance.

4.4. Simulation Results. The obtained simulation results are illustrated in the following figures and discussed hereafter.

(i) Figure 6 shows the monthly energy produced by the PV system and the energy consumption of the load. It is clear that the energy produced by the PV system exceeds the energy consumption during the nine months March-November. The excess-produced energy will be partially used in recharging the battery block and the remaining part in supplying the grid. During the remaining three months, known as lowest solar radiation in the year, the PV energy produced and the load energy consumption are very close which verifies the appropriateness of the performed PV system sizing in Section 3 resulting a PV peak power of 3.2 kW

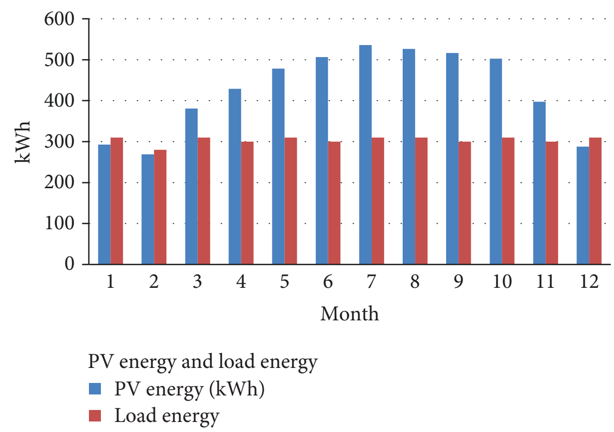

Figure 6: The monthly energy produced by the 3.2 kWp PV system and the load consumption.

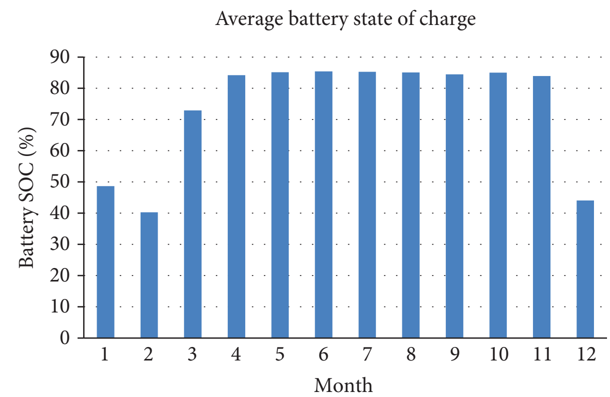

Figure 8: The monthly state of charge of battery block (48/19.2 kWh).

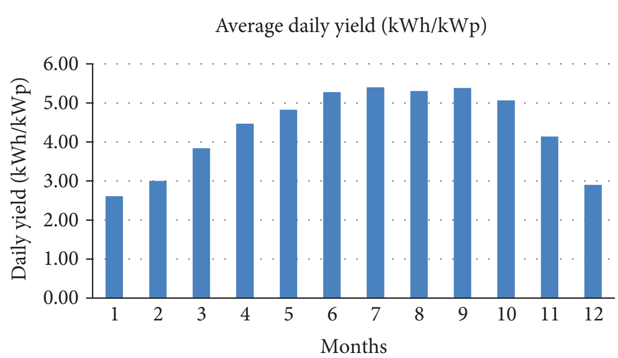

Figure 7: Average daily yield (kWh/kWp).

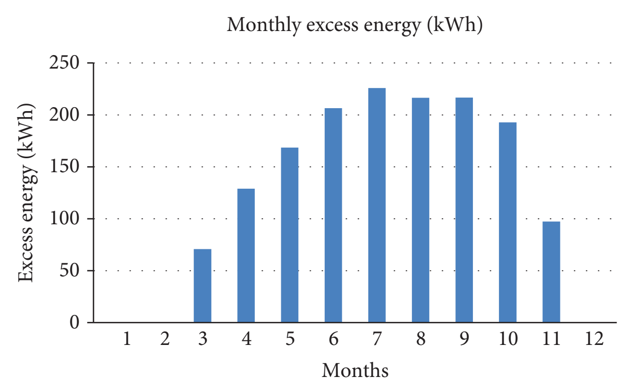

Figure 9: Monthly excess PV energy.

(ii) Figure 7 shows the daily energy yield (kWh/kWp) of the system which varies between 2.6 and 5.4 kWh/kWp in January and July (resp.). This result corresponds to performance ratios amounting to 90% and 66.25% (resp.). The degradation of the performance ratio during summer months as July refers to higher internal PV power losses caused by higher ambient temperature during these months

(iii) Figure 8 illustrates the monthly battery state of charge (SOC) which varies between 40 and 85%. It is noteworthy that its minimum value does not fall short of 40% even during the months of the lowest solar radiation (Dec.-Feb.) and varies in the range of 73-84% during the remaining nine months which verifies the correctness of battery sizing

(iv) Figure 9 shows the produced PV energy which exceeds the load demand during nine months. The excess energy will be injected into the grid when it is available or raise the SOC of the battery block or will be lost when SOC is 100%

(v) Figure 10 shows the hourly simulation of load power consumption, PV power, and SOC (%) during three days in April when the PV output is high due to high solar radiation. It can be observed that the battery SOC remains high since it varies in the range 77-93%. On the other hand, Figure 11 shows the same system parameters during three days in December where the solar radiation is low. It can be seen that the SOC decreases to about 30% during such days

5. Conclusions

(i) The daily energy load of the residential house selected for this study amounting to 10 kWh/day corresponds to the hourly power variation from 200 to 730 W. Based on the obtained simulation results, the energy consumption of this house can be fully covered by a PV system rated at 3.2 kWp with a battery block capacity amounting to 19.2 kWh

(ii) The energy produced by the PV system exceeds clearly the load demand during nine months of the year (Mar.-Nov.) while it is almost equal to the energy of the load during the remaining three months (Dec.–Feb.) which are known of the lowest solar radiation. These results verify the property of the proposed PV system design for solving the power supply in the residential sector in Gaza

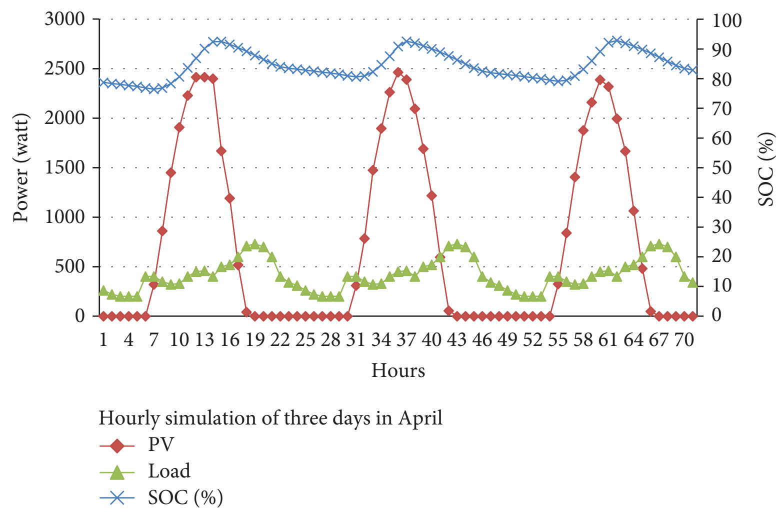

Figure 10: Hourly simulation of load power, PV power, and the battery SOC in three days in April.

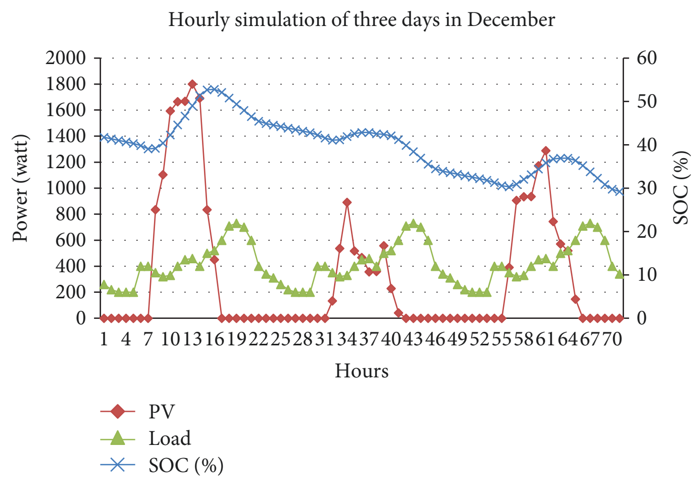

Figure 11: Hourly simulation of load power, PV power, and the battery SOC in three days in December.

(iii) The battery block state of charge varies during nine months (March–Nov.) in the range of 73-85% and during the months (Dec.-Feb.) in the range of 40-49%, which shows that the proposed PV system is able to cover the load demand while keeping the battery state of charge on an acceptable level

(iv) The daily energy yield of the PV system varies between 2.6 and 5.4 kWh/kWp in January and July, respectively, which corresponds to a performance ratio of 90% and 66.25%, respectively. The lower performance ratio in July refers to higher ambient temperature during the summer months

Data Availability

I think the data used to support the findings of this study are included within the article except the hourly solar radiation and temperature data used in the simulation, for one year (8760 readings for each).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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