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Optimal Configuration for Design of Stand-Alone PV System

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ABSTRACT

This paper presents a design for a stand-alone photovoltaic (PV) system to provide the required electricity for a single residential household in rural area in Jordan. The complete design steps for the suggested household loads are carried out. Site radiation data and the electrical load data of a typical household in the considered site are taken into account during the design steps. The reliability of the system is quantified by the loss of load probability. A computer program is developed to simulate the PV system behavior and to numerically find an optimal combination of PV array and battery bank for the design of stand-alone photovoltaic systems in terms of reliability and costs. The program calculates life cycle cost and annualized unit electrical cost. Simulations results showed that a value of loss of load probability LLP can be met by several combinations of PV array and battery storage. The method developed here uniquely determines the optimum configuration that meets the load demand with the minimum cost. The difference between the costs of these combinations is very large. The optimal unit electrical cost of 1 kWh for LLP = 0.049 is \$0.293; while for LLP 0.0027 it is \$0.402. The results of the study encouraged the use of the PV systems to electrify the remote sites in Jordan.

Keywords: Renewable Energy Systems; Photovoltaic Stand-Alone Power System; Sizing; Optimization; Storage; Loss of Load Probability; Life Cycle Cost (LCC)

1. Introduction

Renewable-energy sources are becoming more and more attractive especially with the constant fluctuation in oil prices. Solar has good potential and the direct conversion technology based on solar photovoltaic has several positive attributes especially in remote areas [1-4]. The Photovoltaic (PV) system is considered one of the important alternative sources in this regard. Because PV energy production is clean, freely infinitely available and of high reliability, it is a very attractive power source for many applications, especially in rural and remote areas in Mediterranean countries where they have a large quantity of solar radiation around the year.

Jordan is blessed with an abundance of solar energy. The possible amount of generating power and the scope of thermal applications using solar energy is huge. Most parts of Jordan get 300 days of sunshine per year. This makes the country a very promising place for solar energy utilization [5]. The annual daily average solar irradiance (average insulation intensity on a horizontal surface) ranges between 4 - 7 kWh/m^2, which is one of the highest in the world. This corresponds to a total annual of 1400 - 2300 kWh/m^2 depending upon location. Jordan has successfully completed the plan for electrification for most of the villages through the utility grid. Due to remoteness and cost, for some parts of Jordan it is unlikely that the main grid connection will ever be established. A stand-alone PV system with storage battery will be excellent choice for such areas.

A photovoltaic (PV) cell converts sunlight into electricity. A PV or solar cell is the basic building block of a PV system. An individual PV cell is usually quite small. PV cells are connected together to form larger units called modules which can be connected to form even larger units called arrays. These arrays are connected in parallels and series to meet the required electricity demand. PV arrays produce power only when illuminated, and it is therefore standard to employ a large energy storage mechanism, most commonly a series of rechargeable batteries. To pre-2vent harmful battery over-charge and over-discharge conditions and to drive AC loads, a charge controller and a converter must be implemented.

Sizing of the PV array, inverter and battery bank for a stand-alone PV system is an important part of system design. This part requires solar radiation data for the intended geographical location of the site, load demand and manufacturing data for PV modules, inverters and batteries and their operational efficiencies. Numerous studies have been conducted to develop a sizing method which is both easy to apply and highly reliable [6]. Most of these methods assume constant system load and control the variables that have an influence on the degree of reliability. Methods that are based on the concept of power supply during a number of autonomous days are typically used. These methods are simple and assure the required reliability of the PV system during autonomous days. In these methods, the storage system meets the load demand. The storage system capacity is regarded as a measure of reliability of the PV system. So the reliability is determined by the autonomous days. These methods exhibit no direct relationship between the PV array output and the storage system capacity. Also, the resultant sizing of the combination of PV array and battery bank for a solar PV system is not necessarily optimal. Method based on the study and characterization of daily energy balances is developed [7,8]. More universal results are obtained when implementing these methods. Another method design of a stand-alone PV system is based on the concept of reliability of the power supply to the load, which is usually quantified by the loss of power supply probability (LPSP) [9-17]. This concept is defined as the relationship between the energy deficit and the energy demand during the total operation time of the installation. In statistical terms, the LLP value refers to the probability that the system will be unable to meet energy demand.

Due to the random nature of the energy source, great effort must be made to optimize the design of stand-alone photovoltaic systems in terms of both energy consumption and costs. The cost of RE generation plays a major role in determining the effectiveness of the RE systems. Hernández *et al*. examined the development of the four main renewable energy technologies (RET) in Spain in the latest years: biomass, small hydro (SH), solar photovoltaic (solar PV) and wind [18]. The study concluded that Spain is suitable in meeting the RE generation target but not efficient in costs. The task of sizing should compromise between cost and reliability. Accurate sizing ensures that demand is met and allows costs to be cut in the future. This will allow a practical use of these systems in the renewable energies market. Sizing a PV system means determining both the number and area of modules to install and the capacity or total number of ampere-hours collectable in the battery.

In this work a standard model based on daily energy balance is used to determine system size. Several design criteria are investigated. Numerical methods based on detailed simulations of PV system behavior which are performed over a specific period of time are used. The energy balance of the PV system and the state of charge of the battery are calculated daily. The simulation period is taken to be one year to have statistical significance of the value of loss of load probabilities LLP. A computer program is developed to simulate the PV system behavior and to numerically find an optimal combination of PV array and battery bank for the design of stand-alone photovoltaic systems in terms of reliability and costs. The detailed design and economical analysis of a stand-alone PV system to provide the required electrical energy for a single residential household in Jordan is presented. The considered location is Jordan University of Science and Technology, which is located in the northern part of Jordan.

2. Ease the Household PV System Configuration

The basic configuration of a PV stand-alone system shown in **Figure 1** is considered in this study. The system consists mainly of solar panels, inverter, batteries and load. The function of the PV array is to convert the sunlight directly into DC electrical power. The inverter is used to convert the DC electrical power into AC power; to match the requirements of the common household AC appliances. The excessive part of DC power is stored in the battery to be used when there is no sunshine. The controller monitors the electrical input from the solar panels and controls the amount going directly into the inverter and the amount for charging and discharging of the battery bank.

3. Prepare Site Meteorological Data

To predict the performance of a PV system in a location, it is necessary to collect the meteorological or environmental data for the site location under consideration. The monthly average daily solar radiation data incident on a horizontal surface at the considered site is shown in **Figure 2**. It is clear from **Figure 2** that solar energy incident in the considered site is very high especially during the summer months, where it exceeds 7 kWh/m^2/day on horizontal. **Table 1** lists the average number of clear days for each month and the average number of shining hours for each month. It is clear from **Table 1** that even in winter, Jordan enjoys more than twenty days of sunshine per month. The total number of sunshine days in Jordan exceeds 300 annually.

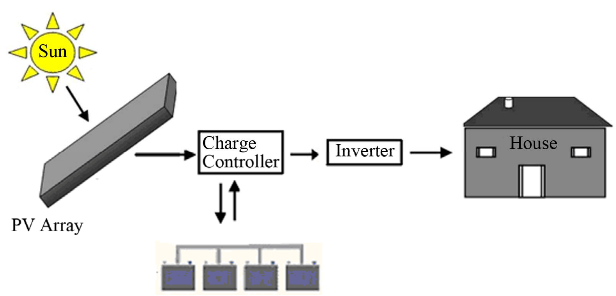

Figure 1. Schematic of stand-alone PV system.

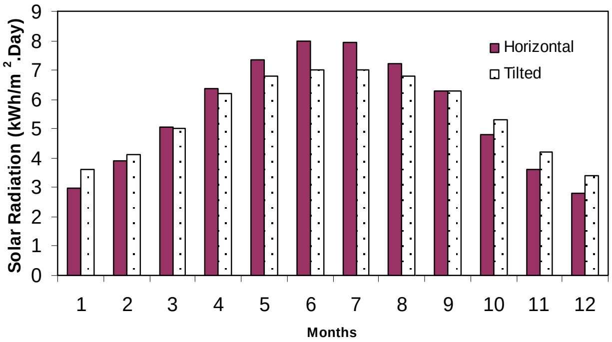

Figure 2. Monthly average daily global radiation (total irradiance) on a horizontal surface and on a 30 º tilted plane at the considered site.

Table 1. Clear days and sunshine hours average numbers.

Month	Average No. of clear days	Average No. of hours of sunshine
January	20	232
February	22	260
March	24	296
April	25	275
May	25	348
June	30	405
July	31	380
August	31	390
September	29	334
October	25	280
November	26	264
December	22	233

4. Electrical Demand

The household in the remote area in Jordan is assumed to be simple—not requiring large quantities of electrical energy. The electrical loads include lighting, medium size refrigerator, one microwave oven and other ordinary household electrical appliances, e.g. TV sets, hair dryers, etc. The daily electrical demand in a typical day for each device is shown in **Table 2**. It is assumed that this load is constant around the year. The corresponding load profile for a typical day is indicated in **Figure 3**. The average daily load demand EL can be calculated from **Table 2** to be 13205 Wh/day.

5. PV System Design

Jordan is a relatively small country. The northern part of Jordan is located near 30.58˚ latitude and 36.23˚ longitude. Tilt angle is defined as the angle of inclination of a module measured from the horizontal. Since the considered site is located at 30.58˚ North latitude and 36.23˚ east longitude, the optimal angle for solar panels is to be 30˚ degree facing south.

Table 2. The Household Load Data.

Electrical Load	No. of units	Operating Hours Per Day	Wattage Per Unit used	Wh/day
Lights	6	12	15	180
Ceiling fan	2	10	100	1000
Washing machine	1	1	375	375
Computer	1	4	225	900
Refrigerator	1	9	600	5400
Microwave	1	0.5	1300	650
TV	1	14	300	4200
Laundry	1	0.5	1000	500
				Total = 13205 Wh/day

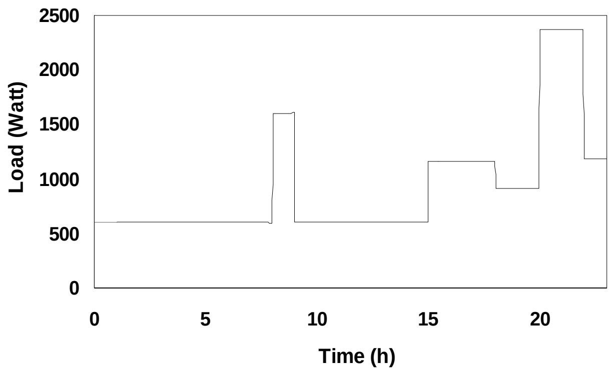

Figure 3. The load profile of the household.

The output of a PV array is related to the light intensity falling on the PV array, ambient temperature, cell temperature, load status and characteristics of PV modules. Since the PV array considered in this study is tilted 30˚ facing south, the hourly global radiation on a horizontal surface should be converted to that on PV modules. Chenni *et al*. developed a simple method to calculate global, diffuse and direct irradiance on vertical and tilted surfaces for all uniform sky conditions (clear sky and overcast sky) [19]. Since the hourly global radiation on a horizontal surface is available, the total irradiance on tilted plane with any orientation can be given using Hay's sky diffusion anisotropic model [20].

$$\left.\begin{aligned} G_\beta &= G_b R_B + 0.5\rho G\left(1-\cos\beta\right) \\ &\quad + G_d\left[R_B\, G_b/G_o + 0.5\left(1-G_b/G_o\right)\left(1+\cos\beta\right)\right] \end{aligned}\right\} \quad (1)$$

where, G is total irradiance on horizontal surface (W/m^2), G_b is direct radiation incident on horizontal surface W/m^2), G_β is total irradiance on tilted surface (W/m^2), G_d is diffuse incident on horizontal surface W/m^2), and R_B the ratio of the direct radiation on the tilted plane to that on a horizontal surface and has the following form:

$$R_B = \cos\theta_i/\cos\theta_z \quad (2)$$

The remaining variables and quantities are determined by:

$$\left.\begin{array}{l}\theta_i = \cos^{-1}\left[\cos\theta_z\cos\beta + \sin\theta_z\sin\beta\cos\left(\gamma_s-\gamma\right)\right],\\ \theta_z = \cos^{-1}\left[\cos\theta\sin\phi + \cos\delta\cos\phi\cos\omega\right],\\ \gamma_s = \sigma_{ew}\sigma_{ns}\gamma_{so} + \left[\dfrac{1-\sigma_{ew}\sigma_{ns}}{2}\right]\sigma_{\omega}180^{\circ},\\ \gamma_{so} = \sin^{-1}\left[\dfrac{\sin\omega\cos\delta}{\sin\theta_z}\right]\\ \sigma_{ew} = \left\{\begin{array}{ll}1 & |\omega| < \omega e_w\\ -1 & \text{otherwise}\end{array}\right\},\quad \sigma_{ns} = \left\{\begin{array}{ll}1 & \phi\left(\phi-\delta\right)\ge 0\\ -1 & \text{otherwise}\end{array}\right\}\\ \sigma_w = \left\{\begin{array}{ll}1 & \omega\ge 0\\ -1 & \text{otherwise}\end{array}\right\},\quad \omega_{ew} = \cos^{-1}\dfrac{\tan\delta}{\tan\phi}\end{array}\right\} \quad (3)$$

where, θ theta is incidence angle of light rays (deg), θ_z is Zenith angle (deg), β is the Tilt angle of plane to gorund (deg), δ is declination of the sun (deg), φ is latitude, γ is azimuth angle of inclidned plane (deg), γ_s is solar azimuth angle (deg), ω is hours angle (deg).

The hourly tilted solar irradiation is calculated using the above Equations (1)-(3). The average monthly tilted irradiation is shown in **Figure 2**.

5.1. Design Criteria

To design a stand-alone PV system for the considered household, the size of the PV array and battery bank capacity should be determined. Two design criteria are used: average daily solar radiation and average lowest month. The ability of the resulting sizes from these two criteria to meet the daily demand is investigated. The size of the PV array used in this study can be calculated by the following equation [21]:

$$\text{PV area} = \frac{E_L}{G_{in}\times\eta_{\text{PV}}\times\text{TCF}\times\eta_{out}} \quad (4)$$

where, G_{in} *is* solar energy input per day on PV panels, TCF is the temperature correction factor, η_{PV} is PV efficiency, η_{out} is battery efficiency (η_B) × inverter efficiency (η_{Inv}).

As for the sizing of the battery, the storage capacity of the battery can be calculated according to the following relation [22,23]:

$$\text{Storage capacity} = \frac{N_c E_L}{\text{DOD}\eta_{out}} \quad (5)$$

where, N_c is number of autonomous days (the largest number of continuous cloudy days of the site). DOD is maximum permissible depth of discharge of the battery. The selected modules are PS-P 60 mono-crystalline silicon (see [24]), with the following specifications at standard test conditions (*i.e.*, 1000 W/m^2 and 25˚C):

-Max Power = 250 W;

-Max Current = 8.17 Amps;

-Max Voltage = 29.4 Volts;

-Nominal Output Voltage 24 Volts;

-PV Efficiency η_{PV} = 14%.

For the first design criteria based on average daily solar radiation, the average daily solar energy input over the year (G_{av}) on a south facing surface tilted at an angle equal to 30˚ is calculated from **Figure 2** to be about 5.475 kWh/m^2·day. If the cell temperature is assumed to reach 45˚C in the field, then the temperature correction factor (TCF) will be 0.9 as indicated in [21]. Assuming battery efficiency η_B = 0.85 and inverter efficiency η_{Inv} = 0.94, then η_{out} = 0.85 ∗ 0.94. Thus, using Equation (4), the PV area is 25.4 m^2, if the largest number of continuous cloudy days Nc in the selected site is about 3 days. Thus, for a maximum depth of discharge for the battery DOD of 0.8, the storage capacity according to Equation (5) is 61.975 kWh. For the second design criteria based on the average lowest month of solar irradiation, **Figure 2** shows that the lowest irradiation corresponds to Dec. with tilted average equal to 3.4 kWh/m^2·day. The design will be based on this value $G_{\min}$. According to equation (4), the PV area is 40.9 m^2. The required storage capacity for five autonomous days is 61.975 kWh.

In order to determine the ability of the resulting sizes from these two criteria to meet the daily demand, the daily amount of charge remaining in the batteries is calculated. The batteries supply the required electricity when there is no direct electricity PV production. The batteries recharge during the daylight if extra energy is available. **Figure 4** shows the daily amount of charge remaining in the batteries for four months in row starting in Oct. On October first, the batteries are assumed to be fully charged. The amount of energy in fully charged batteries is 61.975 kWh. For PV area = 25.4 m^2, the battery completely discharged on Dec. 6 and this failure continued for the next two months. On the other hand, when PV area = 40.9 m^2, the stand-alone PV system meet the required load without any failure. However, if there is a charge controller set to prevent discharging the batteries at 20%, then there will be power out for five nights. For PV area = 25.4 m^2, the amount of extra PV

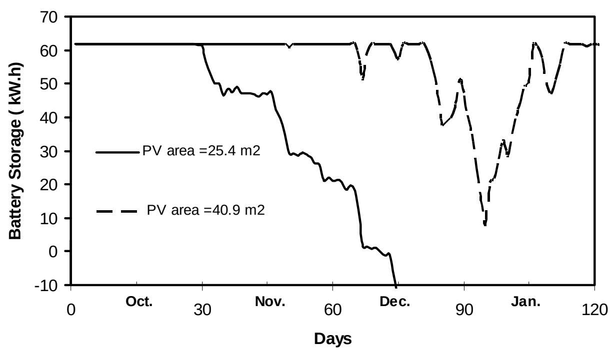

Figure 4. Daily amount of charge remaining in the batteries.

production completely charge the batteries during Oct. However, during November, there is not enough PV production to completely charge the batteries during the daytime. The amount of battery charge kept decreasing during November all the way until it is completely discharged on the beginning of December. It took the system over two months to completely recharge the batteries. As for PV area = 40.9 m^2, the PV production during day is able to completely recharge the batteries until the beginning of December. The amount of energy stored in the batteries stays relatively large except for few days at the beginning of January. After that is increased rapidly.

5.2. Design of the Battery Charge Controller

The primary function of a charge controller in a stand-alone PV system is to maintain the battery at highest possible state of charge while protecting it from overcharge by the array and from over discharge by the loads. Wu *et al*. developed a new fast charging method that is applied to micro-grid photovoltaic systems to eliminate batteries undercharge or overcharge due to random changes of solar radiation [25]. Some PV systems can be effectively designed without the use of charge control. In the present study, a charge control is required due to the fact that the load is unpredictable. Another reason for the charge control is that the battery storage is optimized resulting in undersized system, a charge control is need to prevent the severe discharge resulting in short life of the battery. The algorithm or control strategy of a battery charge controller determines the effectiveness of battery charging and PV array utilization, the ability of the system to meet the load demands and extend the lifetime of a battery. When the irradiation is high (typically during summer), energy generated by the PV array often exceeds the electrical load demand. To prevent battery damage resulting from overcharge, a charge controller is used to protect the battery. A charge controller should prevent overcharge of a battery regardless of the system sizing/design and seasonal changes in the load profile, operating temperatures and solar irradiation. It has to be capable of carrying the short circuit current of the PV array. Thus, in this case, it can be chosen to handle 73.4 A and to maintain the DC bus voltage to about 36 V.

5.3. Design of the Inverter

The selected inverter must be able to handle the maximum expected power of AC loads. The rated power of the inverter Prat, inv taken to be 20% higher than the rated power of the total AC loads that presented in **Table 2**. Thus the rated power of the required inverter will be 1800 W. the specification of the required inverter will be 1800 W, 36 VDC, and 50 Hz.

5.4. Sizing of the Battery

The life of battery is a function of maximum depth of discharge DOD. The maximum depth of discharge for the battery is taken to be 0.8. The sizing method for barratry storage is based on the concept of power supply during a number of autonomous days; during these days the load demand is met solely by the storage system. If the largest number of continuous cloudy days (number of autonomous days) is NC, then the minimum required ampere-hours of the battery Ah_{totB} is calculated by:

$$\mathrm{Ah}_{totB} = \frac{\text{Storage capacity}}{\text{DC nominal voltage}} \tag{6}$$

If the selected battery is lead acid with nominal voltage = 12 Volts and rated capacity = 220 Amp-hrs, then the number of Batteries in Parallel NB_p is calculated by:

$$NB_P = \frac{\mathrm{Ah}_{totB}}{\text{rated capacity}} = \frac{\mathrm{Ah}_{totB}}{220} \tag{7}$$

Three batteries are needed to meet the system nominal voltage. Finally, the total number of batteries s is $NM_P \times NM_S$ batteries.

5.5. Sizing of PV Modules

The numbers of PV modules are determined by the following expressions:

$$\text{Number of modules} = \frac{\mathrm{PV}_{\text{peak power}}}{\text{Peak power of a module}} \tag{8}$$

where $\mathrm{PV}_{\text{peak power}}$ is calculated by

$$\mathrm{PV}_{\text{Peak Power}} = \mathrm{PV}_{\text{area}} \times \mathrm{PSI} \times \eta_{\mathrm{PV}} \tag{9}$$

where PSI is the maximum radiation intensity taken to be 1000 W/m^2, and the peak power of the selected module is 250 W.

The number of modules in parallel NM_p and series are calculated by:

$$\left.\begin{array}{l} NM_p = \dfrac{I_{tot}}{I_M \times D_F}, \quad NM_S = \dfrac{V_S}{V_m}, \quad I_{tot} = \dfrac{\mathrm{Ah}_{tot}}{N_S} \\ \mathrm{DCAh} = \dfrac{E_L}{V_S}, \qquad \mathrm{Ah}_{tot} = \mathrm{DCAh} \times f \end{array}\right\} \tag{10}$$

where,

I_M: Module Operating Current ,

D_F: Module Derate Factor,

I_{tot}: The Total PV Array Current,

E_L: Total System Load,

V_S: System Nominal Voltage,

f: Losses and Safety Factor,

N_S: The Average Number of Solar hrs,

DCAh: The Total DC Amp-hours/Day,

NM_S: Number of Module in Series,

NM_P: Number of Module in Parallel.

N_S is calculated from **Table 1**, to be 6 hours and the system nominal voltage is taken to be 36 volt. The losses and safety factor is assumed to be 1.2.

The total number of modules NM_{tot} is

$$NM_{tot} = NM_P \times NM_S \tag{11}$$

5.6. Sizing Optimization

As mentioned previously, the method presented here is quit simple and quick, but the resulting sizing of the combination of PV array and battery bank for a solar PV system is not necessarily optimal. It is the objective of this section to find a sizing combination that minimizes the cost while maintaining desired values of reliability. The reliability of power supply of system is expressed in terms of the loss of load probability (LLP), defined as the power failure time *Tf* divided by the estimated period of time *T*, *i.e.* LLP = *Tf*/*T*. For the given LLP value of the whole year, many configurations can meet this reliability demand of power supply. In this study, a program for calculating the LLP values and the total cost of different configurations is developed. In the program, a PV area and number of autonomous days are provided to the program. The program calculates the daily PV output for the whole year according to the following equation

$$\text{PV}_{out} = G_{in} \times \text{PV area} \times \eta_{\text{PV}} \times \eta_B \times \eta_{Inv} \tag{12}$$

and compares it with the daily demand E_L. A charge controller is simulated that prevents the both overcharge and the undercharge of batteries bank. The amount charge stored in batteries is calculated daily. A power failure is indicated if the amount of charge reaches the lower limits, which is specified here to be 20% of the storage capacity given by Equation (5). The program counts these times and calculate LLP for the given combination. The program calculates the total number of PV modules (parallels and series) required according to Equations (10) and (11).

The program has calculated the whole year's LLP values of different configurations with PV area changing from 30 m^2 to 50 m^2 and number of autonomous days changing from 1 to 7. The trade-off curves between the numbers of PV modules and number of batteries for several LLPs are shown in **Figure 5**. **Figure 5** shows only parts of calculation results.

The objective function of the optimization problem is the life cycle cost (LCC) of stand-alone PV system. The LCC of any system consists of the total costs of owning and operating it over its lifetime, expressed in today's money. The costs of a stand-alone PV system include acquisition costs, operating costs, maintenance costs, and replacement costs. The LCC of the PV system includes the sum of all the present worth's (PWs) of the costs of the PV modules, storage batteries, battery charger, and inverter, the cost of the installation, and the maintenance and operation cost (M&O) of the system. The details of the used cost data for all items are shown in **Table 3**. These data was obtained from the manufacturer of PV system [26].

The lifetime N of all the items is considered to be 20 years, except that of the battery which is considered to be 5 years. Thus, an extra three groups have to be purchased, after 5 years, 10 years, and 15 years. Assuming an inflation rate *i* of 3% and an interest rate d of 10%.

The program calculates the LLC for any combinations according to the following equations:

PV array cost C_{PV} is given by:

$$C_{\text{PV}} = (2.42\ \$/\text{W}) \cdot \text{PV}_{\text{Peak Power}} \tag{13}$$

where $\text{PV}_{\text{peak power}}$ is calculated by Equation (9)

Initial cost of batteries is given by:

$$C_B = (1\ \$/\text{Ah}) \cdot \text{Ah}_{tot} \tag{14}$$

where Ah_{tot} is the required ampere-hour of the batteries calculated from Equation (6)

$$C_{Inv} = (\$0.5/\text{W}) \cdot P_{rat,inv} \tag{15}$$

The charger cost is given by:

$$C_C = (\$0.5/\text{W}) \cdot I_{SC} \tag{16}$$

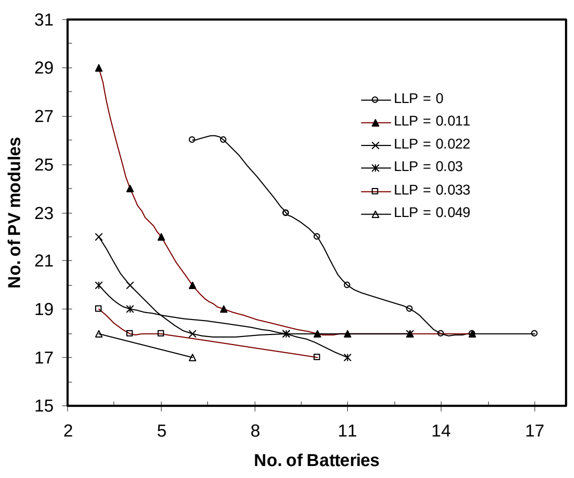

Figure 5. Trade off curves between the numbers of batteries and PV modules for the different LLP values.

Table 3. The used cost of all items.

Item	PV	Battery	Inverter	Charge controller	Installation	M&O/ Year
Cost	2.42 $/W	1$/Ah	0.5 $/W	$3.2/A	10% of PV cost	2% of PV cost

The installation cost is taken to be 10% of the PV cost. As for the current value of the maintenance cost C_{MPW} is calculated by [25]:

$$C_{\text{MPW}} = (\text{M/yr}) \times \left(\frac{1+i}{1+d}\right) \times \frac{1-\left((1+i)/(1+d)\right)^N}{1-(1+i)/(1+d)} \quad (17)$$

The maintenance cost per year (M/yr) is assumed 2% of the PV cost.

The present value of the n^{th} extra group of batteries $C_{Bn\text{PW}}$ purchased after N years is calculated by:

$$C_{Bn\text{PW}} = C_B\left((1+i)/(1+d)\right)^N \quad (18)$$

The LCC of the system is calculated by summing all the above cost, I'e

$$\begin{aligned} \text{LCC} = {} & C_{\text{PV}} + C_B + C_{B1\text{PW}} + C_{B2\text{PW}} \\ & + C_{B3\text{PW}} + C_{Ins} + C_c + C_{inv} + C_{\text{MPW}} \end{aligned} \quad (19)$$

Table 4 list sample of the calculation results output from the program developed. For a given value of LLP there is an optimum configuration that has the lowest cost. For example, for LLP = 0.0027, the cost of the combination that meet this requirement ranges from $22,267 to 26,177. However, the optimum combination is number of batteries = 10 and PV modules = 20. Another example for LLP = 0.033, the cost of the system

Table 4. Sample of the calculation results.

PV area (m^2)	No of autonomous days	Number of Batteries	Number of PV modules	LLP	LLC ($)
35	**4.5**	**11**	**20**	**0.0000**	**23239**
33.5	5	12	19	0.0000	23320
45	3.5	9	26	0.0000	26197
40	6	14	23	0.0000	27714
50	6.5	15	29	0.0000	32920
49.5	7	17	28	0.0000	33446
50	7	17	29	0.0000	33669
34.5	**4**	**10**	**20**	**0.0027**	**22267**
35	4	10	20	0.0027	22490
37	3.5	9	21	0.0027	22632
37.5	3.5	9	22	0.0027	22855
36	4	10	21	0.0027	22935
33	5	12	19	0.0027	23097
49.5	2	5	28	0.0027	25955
50	2	5	29	0.0027	26177
34	**3.5**	**9**	**20**	**0.0055**	**21295**
34.5	3.5	9	20	0.0055	21518
35	3.5	9	20	0.0055	21741
37.5	3	7	22	0.0055	22106
36	3.5	9	21	0.0055	22186
39.5	2.5	6	23	0.0055	22248
38	3	7	22	0.0055	22328
33.5	4.5	11	19	0.0055	22570
43	2	5	25	0.0055	23058
49.5	1.5	4	28	0.0055	25205
50	1.5	4	29	0.0055	25428
34	**3**	**7**	**20**	**0.0082**	**20546**
36	2.5	6	21	0.0082	20688
34.5	3	7	20	0.0082	20769
36.5	2.5	6	21	0.0082	20911
35	3	7	20	0.0082	20991
37	2.5	6	21	0.0082	21134
39.5	2	5	23	0.0082	21498
38	2.5	6	22	0.0082	21579
38.5	2.5	6	22	0.0082	21802
32	5	12	18	0.0082	22651
44	1.5	4	25	0.0082	22755
44.5	1.5	4	25	0.0082	22977
34	**2.5**	**6**	**20**	**0.0110**	**19797**
34.5	2.5	6	20	0.0110	20020
35	2.5	6	20	0.0110	20242
48.5	1	3	28	0.011	24011
50	1	3	29	0.011	24679
34	**2**	**5**	**20**	**0.014**	**19048**
34.5	2	5	20	0.014	19270
35.5	2	5	20	0.014	19716
31	5	12	18	0.014	22206
30.5	6	14	18	0.014	23481
30	7	17	17	0.014	24757
33.5	**2**	**5**	**19**	**0.019**	**18825**
32	2.5	6	18	0.019	18905
37.5	1.5	4	22	0.019	19858
38	1.5	4	22	0.019	20081
31	4	10	18	0.019	20707
31.5	**2.5**	**6**	**18**	**0.022**	**18683**
35	1.5	4	20	0.022	18744
37.5	1	3	22	0.022	19109
38	1	3	22	0.022	19332
31	3.5	9	18	0.022	19958
30.5	5.5	13	18	0.022	22732
34	**1.5**	**4**	**20**	**0.025**	**18298**
30.5	5	12	18	0.025	21983
30	5.5	13	17	0.025	22509
30	6	14	17	0.025	23258
35	**1**	**3**	**20**	**0.027**	**17995**
33.5	1.5	4	19	0.027	18076
30.5	4	10	18	0.027	20484
30.5	4.5	11	18	0.027	21234
30	5	12	17	0.027	21760
34.5	**1**	**3**	**20**	**0.030**	**17772**
33	1.5	4	19	0.030	17853
32	2	5	18	0.030	18156
30	4.5	11	17	0.030	21011
33	**1**	**3**	**19**	**0.033**	**17104**
31.5	1.5	4	18	0.033	17184
34	1	3	20	0.033	17549
31.5	2	5	18	0.033	17934
30	4	10	17	0.033	20262
31	**1**	**3**	**18**	**0.049**	**16212**
30.5	1.5	4	18	0.049	16739
30	2	5	17	0.049	17265
30	2.5	6	17	0.049	18014

ranges from \$17,104 to \$20,262. The optimum combination corresponds to number of batteries = 3 and PV modules = 19. For LLP = 0, the stand-alone system works without any power failure. The optimal cost for such system is \$23,239, which is combined of 11 batteries and 20 PV modules. However, for LLP = 0.049, which means there are 18 nights without power in the whole year. The optimal cost for such system is \$16,212. Knowing this difference can help the designer decided to install another auxiliary hybrid system or not.

It is sometimes useful to calculate the LCC of a system on an annual basis. The annualized LCC (ALCC) of the PV system in terms of the present day dollars can be calculated by:

$$\mathrm{ALCC} = \mathrm{LCC}\left[\left(1-\left(\frac{1+i}{1+d}\right)\right) \Big/ \left(1-\left(\frac{1+i}{1+d}\right)^{N}\right)\right] \quad (20)$$

Unit electrical cost of 1 kWh is $\frac{\mathrm{ALCC}}{365E_L}$.

Table 5 summarizes the optimal configurations and the corresponding unit cost of electricity. The calculated current unit cost of PV systems depends on the LLP values. There values range between 0.419 S/kWh and 0.293 \$/kWh. Although this price is very high compared to the current unit cost of electricity in Jordan (0.114 \$/kWh), it is predicted that this price will drop significantly in the future due to decrease in the initial cost of the PV modules. At the same time, if the future unit cost of electricity in Jordan increases due to the rapid increase in the conventional fuel prices, therefore PV energy generation will be promising in the future house electrification due to its expected future lower unit electricity cost, efficiency increase, and clean energy generation compared to the conventional utility grid.

6. Conclusion

An electrification study for a single residential house in a remote isolated site of Jordan is carried out using a stand-alone PV system. The complete design steps and the life cycle cost analysis of the PV system is presented. A method based on calculating the yearly loss of load probability LLP has been presented for a PV sizing. A computer program that simulates the stand-alone PV system daily behavior is developed. According to local hourly measured meteorological data, load demand, the characteristic and price of the components and reliability requirement on power supply, the optimum configuration which meets the load demand with the minimum cost can be uniquely determined by the program. The unit electrical cost for electrifying a remote isolated house using PV systems is calculated. The results of study indicates that using the optimal configuration for electrifying remote areas in Jordan is beneficial and suitable for long-term investments, especially if the initial prices of the PV systems are decreased and their efficiencies are increased. Therefore, in remote sites that are too far from the Jordanian power grid, it is encouraged to install PV systems to generate electricity.

Table 5. Summary of the optimal configurations size and cost for given LLPs.

PV area (m^2)	No of Autonomous Days	Number of Batteries	Number of PV Modules	LLP	LLC (\$)	Cost of 1 kWh
35	4.5	11	20	0.0000	23239	0.419
34.5	4	10	20	0.0027	22267	0.402
34	3.5	9	20	0.0055	21295	0.384
34	3	7	20	0.0082	20546	0.371
34	2	5	20	0.014	19048	0.344
34.5	1	3	20	0.030	17772	0.321
33	1	3	19	0.033	17104	0.309
31	1	3	18	0.049	16212	0.293

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