

## Stand-alone photovoltaic system for an emergency health clinic

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**Abstract.** This paper presents a study and design of a complete stand-alone photovoltaic (PV) system for providing the electrical loads in an emergency health clinic according to their energy requirements. Typical energy consumption daily profiles for the four seasons are assumed. The PV system is optimally sized to be an optimal economic system. Homer software is used as the sizing and optimization tool to determine the size and specifications of photovoltaic system components, system cost and estimation of corresponding produced electrical energy. The results show that the sizing of PV stand-alone system depends on the load data, the solar resource data and the investment cost of system components. Also it is found that providing electricity to the emergency health clinic using PV system is very beneficial and economical, especially considering the decreasing prices of PV systems and their increasing efficiencies and reliability. They have also the advantage of maintaining a clean environment.

### Key words

Photovoltaic systems, Stand-alone, Health clinics, Sizing, Economics

### 1. Introduction

Conventional methods of generating electricity can produce pollutants such as carbon dioxide, the main gas responsible for global warming. The only resource needed to power a solar cell is sunlight; through the photovoltaic effect the energy contained in the sun light can be converted directly to electrical energy. Photovoltaic systems represent a silent, safe, not pollutant and renewable source of electrical energy [1]. This paper provides a design of stand-alone PV system for an emergency health clinic in the Kharga Oasis including suggested load profiles, sizing of a stand-alone PV system for supplying the electrical load of the clinic and provides the economic estimation of the system. US National Renewable Energy Laboratory (NREL)'s, Hybrid Optimization Model for Electric Renewables (Homer) has been used as the sizing and optimization software tool. It contains a number of energy component models and evaluates suitable technology options based

on cost and availability of resource [2]. Analysis with Homer requires information on solar resource, economic constraints, and control methods. It also requires input on component types, their numbers, costs, efficiency, lifetime, etc. Sensitivity analysis could be done with variables having a range of values instead of a specific number. This allows one to ascertain the effects of change in a certain parameter on the over all system.

### 2. Design of The Clinic

Most of the emergency health clinics that are found in rural and remote areas require an environmentally clean power supply. At the same time, the electrical load of the health clinics is critical and requires continuity of the power supply. In Egypt, there are many new projects such as those carried out in New Valley in the western desert of Egypt which will be accompanied by a new population [3]. From this point of view, it is important to introduce a model for an emergency health clinic powered by using photovoltaic system. The Kharga Oasis was selected as the site under consideration. The clinic provides services such as normal examination and emergency medical care. The clinic requires electricity for domestic load such as lighting, communication, refrigeration, and emergency medical devices. While the electrical load of the emergency room consists of emergency medical devices such as ICU monitor, Ventilator, Nebulizer, Electric suction and Autoclave. The total load demand of this clinic is 2000 watt.

### 3. Stand-Alone PV System Sizing

Sizing of stand-alone PV system starts by estimating the energy consumption of the clinic and the available solar energy radiation of the selected location. The sizing procedure is as follow [4]:

#### A. Radiation Data

To get optimum design of PV system, it is important to collect meteorological data (solar radiation and temperature) for the site under consideration (the Kharga Oasis). Table I shows the monthly average values of

global solar radiation over the Kharga Oasis [5]. It is clear from the figure that solar energy incident on the region is very high especially during summer months with average daily radiation during June 8.02 KWh/m<sup>2</sup>/day where the annual average global solar radiation is 6.303 KWh/m<sup>2</sup>/day.

Table I - The monthly average values of daily global solar radiation (Kwh/m/day) in the Kharga Oasis

| Month     | Daily Radiation in Kwh/m <sup>2</sup> /day |
|-----------|--|
| January   | 4.43                                       |
| February  | 5.43                                       |
| March     | 6.38                                       |
| April     | 7.71                                       |
| May       | 7.66                                       |
| June      | 8.02                                       |
| July      | 7.9  |
| August    | 7.45                                       |
| September | 6.7  |
| October   | 5.64                                       |
| November  | 4.68                                       |
| December  | 4.13                                       |

### B. Load Data

The emergency health clinic is suggested to operate two intervals during the day. The daily load profiles were determined by calculating the power demand (Kwh/day) for all load types in the clinic during the four seasons. The estimated daily energy consumption is given in Table II.

Figure (1) shows a typical daily load profiles during the four seasons. It is shown that, summer has the highest energy consumption (16.44 KWh /day) compared to the other seasons. The average annual load energy is 15.16 KWh /day.

Table II - The daily load energy consumption for the clinic

| Load type                      | No. of units | Rated power (W) | Summer           |           | Autumn           |           | Winter           |           | Spring           |           |
|--------------------------------|--------------|-----------------|------------------|-----------|------------------|-----------|------------------|-----------|------------------|-----------|
|                                |              |                 | Hours used / day | KWh / day | Hours used / day | KWh / day | Hours used / day | KWh / day | Hours used / day | KWh / day |
| Communication                  | 1            | 30              | 24               | 0.72      | 24               | 0.72      | 24               | 0.72      | 24               | 0.72      |
| Refrigerators                  | 2            | 200             | 24               | 4.8       | 24               | 4.8       | 24               | 4.8       | 24               | 4.8       |
| Outdoor lighting               | 1            | 20              | 11               | 0.22      | 12               | 0.24      | 13               | 0.26      | 12               | 0.24      |
| Indoor lighting                | 14           | 280             | 4                | 1.12      | 4                | 1.12      | 4                | 1.12      | 3                | 0.84      |
|                                |              | 120             | 7                | 0.84      | 7                | 0.84      | 7                | 0.84      | 7                | 0.84      |
|                                |              | 40              | 13               | 0.52      | 13               | 0.52      | 13               | 0.52      | 14               | 0.56      |
| Fans                           | 3            | 120             | 9                | 1.08      | 9                | 1.08      | ——               | ——        | 8                | 0.96      |
|                                |              | 80              | 6                | 0.48      | 5                | 0.4       | ——               | ——        | 6                | 0.48      |
|                                |              | 40              | 9                | 0.36      | ——               | ——        | ——               | ——        | ——               | ——        |
| Small kettle                   | 1            | 200             | 3                | 0.6       | 3                | 0.6       | 3                | 0.6       | 3                | 0.6       |
| Emergency room electrical load | 1            | 700             | 8                | 4.8       | 7                | 4.18      | 7                | 3.9       | 7                | 4.18      |
| Autoclave                      | 1            | 450             | 2                | 0.9       | 2                | 0.9       | 2                | 0.9       | 2                | 0.9       |
| Total KWh / day                |              |                 |                  | 16.44     |                  | 15.4      |                  | 13.66     |                  | 15.12     |

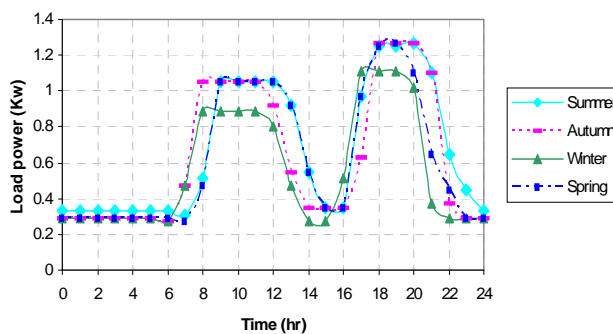


Fig.1. Daily load profiles during the year

### C. PV Array Sizing

The PV array output power ( $P_{PV\ array}$ ) is determined by Eq (1) [3, 6].

$$P_{PV\ array} = \frac{E_L}{\eta_{B.O} \times K_{Loss} \times I} \times PSI \quad (1)$$

where,

$$\eta_{B.O} = \eta_{Inverter\ losses} \times \eta_{Wiring\ losses} \quad (2)$$

Where  $E_L$  is the average daily load energy consumption KWh/day,  $I$  is the average solar radiation incident over the Kharga Oasis in KWh/m<sup>2</sup>/day,  $PSI$  is the peak solar intensity at the earth's surface (1000 W/m<sup>2</sup>),  $\eta_{B.O}$  is the efficiency of balance of system and can be determined by Eq (2) and  $K_{Loss}$  is a factor determined by the different losses such as: module temperature losses, circuit losses, dust, etc. Typical values for  $\eta_{Inverter\ losses}$ ,  $\eta_{Wiring\ losses}$  and  $K_{Loss}$  are 15%, 10% and 90% respectively [6].

### 1) Modules in series

The number of modules in series ( $N_s$ ) as given in Eq (3) is determined by dividing the designed system voltage  $V_{System}$  (usually determined by the battery bank or the inverter) and the nominal module voltage  $V_{Module}$  at standard test conditions (STC) [6].

$$N_s = \frac{V_{System}}{V_{Module}} \quad (3)$$

### 2) Strings in parallel

The number of strings in parallel ( $N_p$ ) as given in Eq (4) is determined by dividing the designed array output  $P_{PVarray}$  by the selected module output  $P_{Modulemax}$  and the number of series modules  $N_s$  [6].

$$N_p = \frac{P_{PVarray}}{N_s \times P_{Modulemax}} \quad (4)$$

### D. Battery Sizing

The storage battery can be calculated using the following equation [3]:

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

Where,

$N_c$  is the number of continuous cloudy days in the selected region (4 days),  $E_L$  is the load energy in Wh, DOD is the depth of discharge (0.7) and  $\eta_{out}$  is equal to 0.765.

### E. Inverter sizing

The function of an inverter is to convert the DC voltage to AC voltage of desired magnitude and frequency [4]. In stand-alone PV systems the inverter is chosen to be 20% higher than the rated power of the summation of AC loads [3].

## 4. Economic Estimation

The price of the PV system and its installation are important factors in the economics of PV systems. These include the prices of PV modules, the control unit, the inverter, and all other auxiliaries. The cost of installation must be taken into consideration. For the present PV system, the life cycle cost (LCC) will be estimated as Eq (6) [7, 8].

$$LCC = IC + OM + R - S \quad (6)$$

Where IC is the initial capital cost, OM is the operation and maintenance cost, R is the repair and replacement cost and S is the salvage value. In this paper, all the costs

are converted to present worth value as given in Eq (7) and Eq (8) [7,8] for the single present value (replacement cost and salvage value) and for the uniform present value (maintenance cost), respectively

$$P = \frac{F}{(1+i)^N} \quad (7)$$

$$P = \frac{A}{CRF} \quad (8)$$

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (9)$$

where, P is the present worth for the sum of money, F is the single payment, A is the annual payment, i is the interest rate, N is the project life time and CRF is the capital recovery factor.

## 5. Homer Analysis

A stand-alone PV system consists of a primary renewable energy source (solar energy), batteries for energy storage and power inverter to maintain the flow of energy between the AC and DC sides. Figure (2) shows the proposed scheme as implemented in the Homer simulation tool. Monthly average data of global solar radiation in the Kharga Oasis are used as the solar energy resource at Lat.N. 25° 27' [5]. Different sizes for PV arrays are considered from 0 to 4 KW and the same sizes are considered for the inverter.

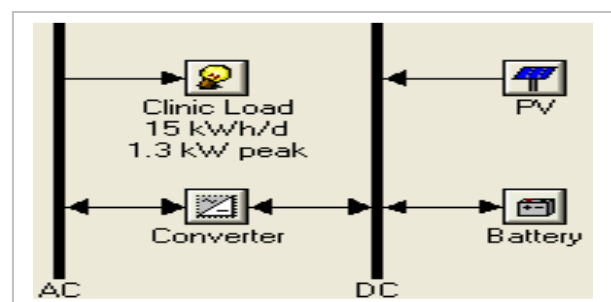


Fig.2. Homer implementation of the stand-alone PV system

### A. Economics and constraints

The installation, replacement and maintenance cost of all components of photovoltaic system are shown in Table III [2, 9]. The life time of PV arrays is 25 years and typical value for the interest rate is 8%. For the battery commercially available models such as Surrette Battery Engineering's Surrette™ 6CS25P models (6 V, 1156 Ah, 6.94 Kwh) are considered in the model.

Table III - Cost of different components of PV system

| Rated capacity | Initial cost | Replacement cost | Operation and maintenance cost |
|----------------|--------------|------------------|--------------------------------|
| PV             | 5000 \$/KW   | 4000 \$/KW       | 0 \$/year                      |
| Inverter       | 800 \$/KW    | 750 \$/KW        | 40 \$/year                     |
| Battery        | 150 \$/KWh   | 150 \$/KWh       | 5 \$/year                      |

## 6. Optimization Results

Table IV shows the optimization search space for the stand-alone system. Homer mixes and matches these components to find what combination satisfies the load requirements at the lowest net present cost. The cost minimizing function is given as the following equation [9]:

$$\text{Minimize annualized cost} = \sum_{i=1}^n (IC_i + R_i + OM_i)$$

Subject to  $\sum (\text{load} - \text{power output}) \leq \text{max unserved load} (\%) * \text{Load}$  (10)

Where IC is the initial capital cost, R is the replacement cost, and OM is the annual operation and maintenance cost. In this analysis, the annualized capital cost is calculated by evenly spreading the initial capital costs and the fixed operating costs of a component over a projects expected lifetime. In addition, the levelized cost of energy (LCOE) and net present cost (NPC) for the cost-minimizing stand-alone system are also calculated. In this optimization process, various sizes of power inverters, and batteries were included in the search space of the program. Several runs were made before determining the optimum sizes of equipment we needed to include to get the best results.

Table IV - Optimization search space for the stand-alone PV system

| PV Array [kW] | Batteries [Quantity] | Converter [kW] |
|---------------|----------------------|----------------|
| 0.000         | 0                    | 0.00           |
| 2.000         | 20                   | 1.00           |
| 2.500         | 30                   | 2.00           |
| 3.000         | 40                   | 3.00           |
| 3.200         |                      | 4.00           |
| 3.300         |                      |                |
| 3.400         |                      |                |
| 3.600         |                      |                |
| 3.800         |                      |                |
| 4.000         |                      |                |

Figure (3) shows the optimization result for the given solar radiation (in the Kharga Oasis), load data (an emergency health clinic), economics and constraints, Homer simulates one optimal configuration from the given search space. This configuration is a stand-alone PV system that supplies the electrical energy to the load with the lowest net present cost.

| PV (kW) | Batt. (kWh) | Conv. (kW) | Disp. Strgy | Initial Capital | Operating Cost (\$/yr) | Total NPC | COE (\$/kWh) | Ren. Frac. |
|---------|-------------|------------|-------------|-----------------|------------------------|-----------|--------------|------------|
| 3.3     | 20          | 2          | CC          | \$38,700        | 941                    | \$48,749  | 0.823        | 1.00       |

Fig.3. The optimization result of homer

### A. Sizing results

The optimum size of PV array results from Homer simulation is 3.3 KW. The number of series modules and parallel strings are calculated by Eq (3) and Eq (4) according to Siemens SP75 PV module. The number of series modules  $N_s$  are 2 and the number of parallel strings  $N_p$  are 22.

The optimum size of inverter is 2 KW and the number of batteries used is 20 (6V, 1156 Ah, 6.94 KWh) battery.

### B. Cost results

The cost results of the system are shown in Fig (4). The initial capital cost is 38700 \$ where the replacement cost is 7408 \$ and the maintenance cost is 4387 \$. The total net present value of the system is 48749 \$.

| Component | Capital (\$) | Replacement (\$) | O&M (\$) | Fuel (\$) | Salvage (\$) | Total (\$) |
|-----------|--------------|------------------|----------|-----------|--------------|------------|
| PV        | 23,100       | 0                | 2,466    | 0         | 0            | 25,566     |
| Battery   | 14,000       | 6,935            | 1,067    | 0         | -1,673       | 20,330     |
| Converter | 1,600        | 473              | 854      | 0         | -73          | 2,854      |
| System    | 38,700       | 7,408            | 4,387    | 0         | -1,746       | 48,749     |

Fig.4. Stand-alone PV system cost result

### C. Annual Electrical Energy Production

The annual output energy production of PV array is 7353 KWh, the annual electrical load served is 5548 KWh, the total amount of energy that cycled through the battery bank during the year (annual throughput) is 3579 KWh/year and the excess electricity is 440 KWh/year about 5.99% of the total PV energy production. Figures (5), (6), (7) and (8) shows the daily profiles during the four seasons for the load power, the PV array output, battery input power and excess electricity. It is clear from figures that spring has the highest PV output power and so it has the maximum excess electricity, while winter has the minimum PV output power and summer is the season with the lowest excess electricity.

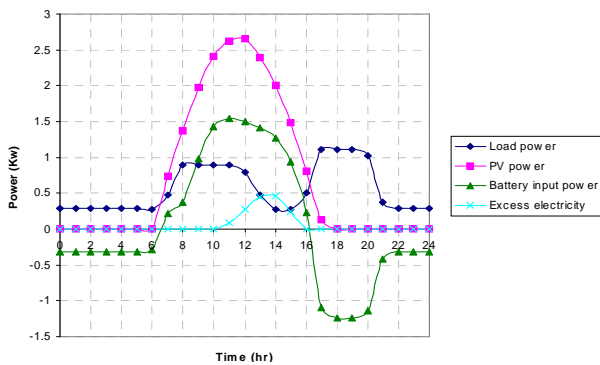


Fig.5. Load power, PV output power, battery input power and excess electricity for a typical day in winter

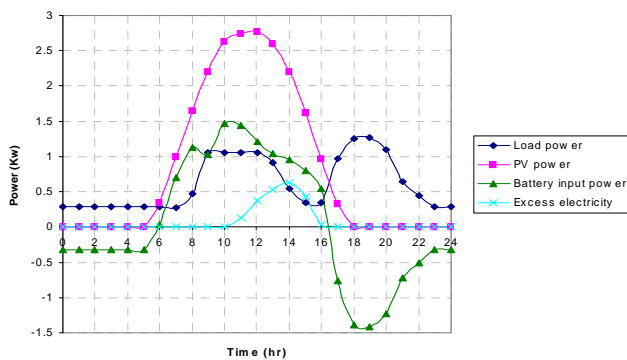


Fig.6. Load power, PV output power, battery input power and excess electricity for a typical day in spring

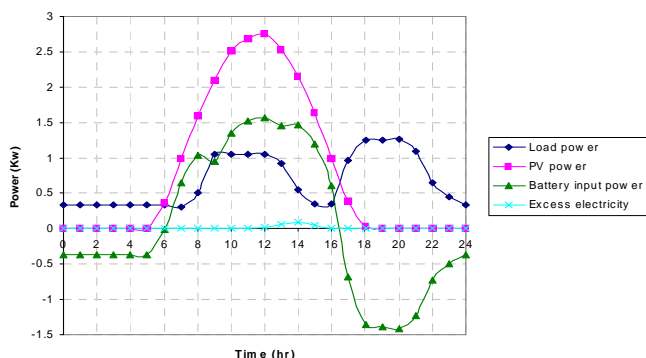


Fig.7. Load power, PV output power, battery input power and excess electricity for a typical day in summer

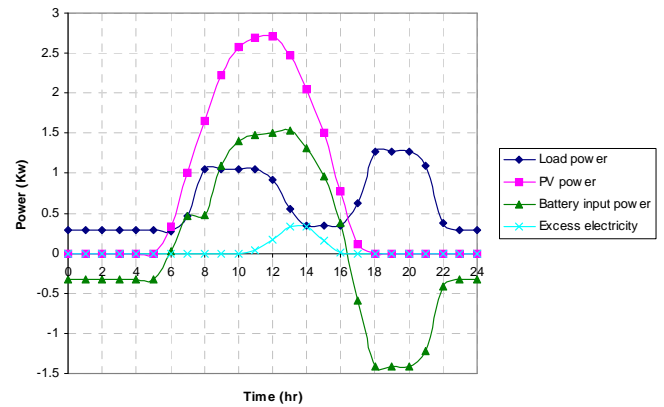


Fig.8. Load power, PV output power, battery input power and excess electricity for a typical day in autumn

## 7. Conclusion

In this paper, a design of a stand-alone PV system for supplying the electrical load of an emergency health clinic in the Kharga Oasis was presented. An optimization model developed by the US National Renewable Energy Laboratory was used to evaluate the stand-alone PV system for supplying the electrical load of the clinic. This includes sizing, simulation and economic estimation of the system. The results show that grid connected PV system sizing depends on load data, solar radiation, investment cost of the system components. The results show that a 3.3 KW PV array capacity and 20 (6V, 1156 Ah, 6.94 Kwh) batteries are needed to supply the electrical load of the clinic. It is clear from electrical energy production that spring is the best season for the performance of the PV system in the Kharga Oasis. PV systems are renewable and environmental friendly power sources that contribute in reducing the green house gas emissions.

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