A Comparison of Simplified and Statistical Methods of Sizing Photovoltaic Installation for a Remote Dwelling in the Saharan Region

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Abstract

This paper discusses two main methodologies of sizing photovoltaic installations and provides a comparative analysis in terms of the accuracy and feasibility of these two methodologies. One of these two methodologies is a simplified approach requiring very little data and information and is based on some assumptions. The other, the loss-of-load probability method is statistically based; it is much more elaborate and requires a complex set of data. Our study shows that for a moderate PV installation to provide basic electrical needs of a small to medium-size detached family house, the simplified method is well suited for such conditions.

Key words: photovoltaic installation, array size, simplified method, loss-of-load statistical method

1. Introduction

The use of solar energy has known some significant growth worldwide and especially in the developing countries because of the abundance of such energy in these countries. The production of photovoltaic (PV) solar energy has exceeded 350 MW in 2003 statistics and it is one of the most promising of the renewable energies as it is clean, abundant, easily decentralized and offers various possibilities of utilization. PV installations have, however, some disadvantages. They tend to have a high initial investment cost which is directly proportional to the size of the system. Storage of the electric energy produced is not 100% efficient, and tends to be quite onerous as well. Therefore and in order to maximize the economic feasibility of PV installations, it is necessary to optimize their size. Such task involves finding the least costly combination of array size and storage capacity that meets the needed load requirements (Sidrach-de-Cardona and Lopez, 1998).

One of the most important parameters in sizing a PV installation is arguably the array size (Lewis, 1996). Several methods for sizing PV installations have been proposed varying in the degree of accuracy and the amount of input data necessary. The majority

of these methods can be grouped into the simplified and the more elaborate groups of methods.

The simplified methods typically require little initial input data. They can provide optimum system size information with differing degrees of success and reliability (Pufrey, 1978; Buresh, 1983). Other more elaborate methods such as the analytical ones, also known as the loss-of-load methods (LLP) have been proposed by Barra et al. (1984), Bartoli et al. (1984) as well as others. These methods rely on data from daily global irradiation series. LLP method requires several input information, namely the annual typical load requirements, current and voltage characteristics of the types of modules used in the system, mean daily irradiation on the plane of the array, tilt factor, maximum number of clear and cloudy days, mean seasonal ambient temperatures, estimated cell temperature rise, energy losses in the battery and the array, among other information (Bhuiyan and Sagar, 2003).

In developing countries many of the technical and meteorological information may not always be available, especially in those isolated and remote areas away from the large urban centers. Furthermore, load requirements for dwellings in such areas tend to be

simple and quite predictable, and not as elaborate and varied as in dwelling in large cities of the developed countries (Benatallah, 1994). Therefore and based on this assumption and context, we intend to compare in this paper the appropriateness of using either sizing approach, namely the simplified method or the LLP. We developed two simulation models using already established theoretical algorithms. The context used in our study is a detached family house with three different levels of loads in an isolated region of the Algerian Sahara, near the town of Adrar (27°88' N; 0°28' E).

2. Theoretical Background

Simplified method

The simplified method is intended to be used as a rough estimation when detailed data of the PV installation and conditions of exploitation are not fully known. It consists first of determining the required average load output of the installation. The number of array branches in series and parallel is calculated according to the estimated annual load. The battery capacity is then calculated based on a predetermined desired number of days of autonomy of the installation. The algorithmic process is as follows:

Step 1 - Estimate the array size

The number of branches in series is determined by the operating voltage of the installation. Once the average required annual load to be supplied is known, the array size (A_g) is determined based on mean daily irradiation on the PV array (Φ_b) and a security factor "k" that accounts for the number of cloudy days and other correction measures and losses due to the efficiency of various system components. Based on experience, factor "k" typically ranges between 0.5 and 0.85 for the Saharan region of N Africa due to large number of clear days per annum (Noton et al, 1998, Barra et al, 1984).

$$A_g = k \Phi_b \quad (1)$$

Where:

Φ_b = mean daily irradiation on the PV array (w/m²)

k = security factor

The array size (P_g) expressed in watts can also be expressed in terms of the annual average equivalent hours per day (h_{eq}) or in other words the annual average watt-hours received per peak watt of the flat-plate PV module per day at the site of installation:

$$P_g = I \cdot V_f \cdot h_{eq} \cdot S \cdot \mu \quad (2)$$

Where:

I = current through an array module (amps)

V_f = module voltage under normal conditions (volts)

S = insolation period (hours)

μ = overall efficiency of system.

Knowing the load output, we can determine the number of branches in parallel (N_p) such as:

$$N_p \geq P_s / P_g$$

Where P_s = required load (W)

Once the number of modules in series (N_s) and in parallel (N_p) is determined, and knowing the manufacturer' surface area of each module (A_m), the total array surface area (A_g) can be expressed as (Puffrey, 1978; Menicucci, 1988)

$$A_g = N_p \cdot N_s \cdot A_m \quad (3)$$

Step 2 - Determine the battery bank storage capacity

The battery bank storage capacity (C_b) needed to overcome the energy deficit during the times when there is no sun is calculated using the worst month in terms of sunlight probability. The minimum battery bank capacity (C_{min}) represents the sum of the difference between the total power output (P_s) and the required load (P_g) for the month "i":

$$C_{min} = \sum (P_{si} - P_{gi}) \quad (4)$$

Furthermore, and in order to account for the efficiency of the system, the various component losses, and the days when there is no sun, a correction factor (η_b) must be used to account for the allowable depth of discharge (D_d) and the factor of discharge (F_d), number of days of full autonomy (N_a), and the number of hours operation of the battery bank (H). The battery bank capacity may be expressed as:

$$C_b = \frac{P_g \cdot N_a \cdot H}{\eta_b \cdot D_d \cdot F_d} (wh) \quad (5)$$

3. Statistical Method

This statistical method is also known as the loss-of-load probability (LLP) method (Egidio and Lorenzo, 1992). This method has been widely written about unlike the simple method. It requires a fairly extensive database of site's solar radiation spanning several years (Barra, 1984). The underlying premise consists of determining the fraction of the required load not supplied by the PV installation depending on the dwelling demand and site conditions. Then we determine the size of the array and the battery bank storage capacity as a function of the load not supplied by the installation. This can be established by the following:

$$(X_m - Y_m) (1 - Y_m) = f(\tau) \quad (6)$$

Where,

X_m = is the maximum fraction of the load sup-

plied by the array.

Y_m = is the fraction of load not supplied by the array

τ = is the maximum battery bank capacity according to the load

The normalized array output per unit area (I_m) can be expressed as a function of X_m , the array size (A_g), or also as function of the local latitude (Φ), array inclination (β), array efficiency (η_g), and the battery efficiency (η_b).

$$I_m = \frac{X_m}{A_g} = \frac{\Phi \beta \cdot \eta_g \cdot \eta_b}{P_s} \quad (7)$$

The normalized battery bank capacity per unit area (J_m) is function of clear sky factor (k_m), length of day (d_m), battery bank efficiency (η_b) and the load demand (P_s).

$$J_m = \frac{\tau}{C_b} = \frac{k_m \cdot d_m \cdot \eta_b}{P_s} \quad (8)$$

Or

$$A_g = \frac{Y_m}{I_m} + \frac{\alpha \cdot J_m^{-\beta} \cdot C_b^{-\beta}}{I_m \cdot (1 - Y_m)} \quad (9)$$

The total cost of system (C_T) is calculated as follows:

$$C_T = a \cdot A_g + b \cdot C_b + D \quad (10)$$

With:

- a : unit cost of each system branch expressed in (\$/m²);
- b : cost of 1 Kwh of storage (\$/Kwh);
- C_b : Storage capacity
- D : other miscellaneous cost items.

Therefore, LLP method consists of minimizing the cost of the system and at finding the appropriate area of generator branch (A_g) and the battery storage capacity (C_b) that fulfill the load demand given the site

condition (Lewis, 1996).

3.1. Area and Optimal Capacity

The optimal array size and corresponding battery storage capacity can be determined according to the following condition:

$$\partial C_T / \partial A_g = 0 \text{ and } \partial C_T / \partial C_b = 0 \quad (11)$$

With deduction, we determine the optimal area (A_{op}) to be:

$$A_{op} = \frac{Y_m}{I_m} + \left\{ \left(\beta \cdot I \cdot \frac{a}{b} \right)^{-\beta} \cdot \frac{\alpha}{I_m \cdot (1 - Y_m)} \right\}^{1/(1+\beta)} \quad (12)$$

And optimal capacity (C_{op}) to be:

$$C_{op} = \left\{ J_m^{-\beta} - \frac{a \cdot \alpha}{b \cdot I_m (1 - Y_m)} \cdot \beta \right\}^{1/(1+\beta)} \quad (13)$$

The constant values of α and β will be determined by comparing experimental and simulation data.

4. Case-Study and Comparison of Simplified and Statistical Methods

Using a simulation program written in Pascal language, a comparison of the two sizing methods were undertaken. Three detached individual houses of low, medium and high-load demand were used for this comparison. The houses are situated in the remote Saharan city of Adrar, Algeria (27°52'N latitude and 0°20'E longitude). The solar radiation characteristics of the site and length of day are shown in Table 1. The scenario is to supply the required power for the three dwellings as shown in Tables 2, 3, 4, 5, 6 and 7. The sizing of the installation is based on the least favorable month in terms of solar radiation (I_m). The number of modules in series for this installation is assumed constant and fixed at 2.

Table 1. Solar radiation characteristics of the site of Adrar

Month	Length of Day	Ratio of insolation period per day per month	Clear sky coefficient (K_t)	Horizontal irradiation (G_h) (wh/m ²)
January	10 h 27 min	0.88	0.68	4340
February	11 h 06 min	0.87	0.69	5346
March	11 h 52 min	0.93	0.73	6740
April	12 h 41 min	0.93	0.73	7676
May	13 h 23 min	0.89	0.70	7934
June	13 h 44 min	0.92	0.71	8202
July	13 h 35 min	0.94	0.71	8108
August	13 h 00	0.91	0.69	7516
September	12 h 14 min	0.88	0.67	6586
October	11 h 25 min	0.86	0.66	5450
November	10 h 40 min	0.86	0.65	4430
December	10 h 17 min	0.86	0.65	3932

Table 2. Characteristics of the equipment for the low-load dwelling

	Duration of operation (Hr/Day)	Average power of equipment (w)	Average Power Demand (w/Day)
Lighting	4	30 (4 lamps)	480
Refrigeration	24	25	600
Television	4	50	200
Radio	3	10	30
Other appliances	0	0	0
Total Demand			1310

Table 3. Characteristics of the equipment for the average-load dwelling

	Duration of operation (Hr/Day)	Average power of equipment (w)	Average Power Demand (w/Day)
Lighting	5	30 (5 lamps)	750
Refrigeration	24	25	600
Television	4	50	200
Radio	4	10	40
Other appliances	4	300	1200
Total Demand			2790

Table 4. Characteristics of the equipment for the high-load dwelling

	Duration of operation (Hr/Day)	Average power of equipment (w)	Average Power Demand (w/Day)
Lighting	5	30 (6 lamps)	900
Refrigeration	24	25	600
Television	4	50	200
Radio	4	10	40
Other appliances	4	300	1200
Total Demand			2940

Table 5. Monthly load demand for the low-load house

Month	Flux (kw/m ² /j)	Monthly Consumption (KW)	Normalized array output per unit area (I _m)	Normalized battery bank capacity per unit area (J _m)
January	6.49	1.33	0.41477	0.18534
February	7.124	1.29	0.46941	0.20888
March	7.9120	1.26	0.53375	0.23611
April	7.900	1.24	0.54153	0.25843
May	7.376	1.28	0.48981	0.25566
June	7.2620	1.34	0.46065	0.25183
July	7.3280	1.36	0.4580	0.24625
August	7.370	1.39	0.45068	0.22809
September	7.264	1.30	0.47495	0.22100
October	6.866	1.28	0.45595	0.20520
November	6.342	1.20	0.44922	0.19904
December	6.05	1.32	0.38958	0.17708

5. Results and Conclusion

The results of the simplified approach and the loss-of-load probability approach as presented in table 8 and 9 indicated very little difference when sizing a stand alone PV installation and the battery storage capacity for a relatively low demand dwelling. Even the high-load dwelling simulated in our conditions may be considered as low compared to an urban

dwelling with more appliances and electrical equipment. Our simulation indicates that there is no need to use highly sophisticated sizing methods and that the simplified approach may be suitable in these condition and especially in underdeveloped countries where data necessary to use the more sophisticated approaches are not available.

Table 6. Monthly load demand for the medium-load house

Month	Flux (kw/m ² /j)	Monthly Consumption (KW)	Normalized array output per unit area (I _m)	Normalized battery bank capacity per unit area (J _m)
January	6.49	2.19	0.25189	0.11256
February	7.124	2.12	0.28563	0.12710
March	7.9120	1.90	0.35396	0.15658
April	7.900	1.86	0.36102	0.17228
May	7.376	1.91	0.32825	0.17134
June	7.2620	2.00	0.30864	0.16873
July	7.3280	2.26	0.27561	0.14819
August	7.370	2.31	0.27119	0.13725
September	7.264	2.28	0.27081	0.12601
October	6.866	2.24	0.26054	0.11725
November	6.342	2.20	0.24503	0.10857
December	6.05	2.18	0.23589	0.10722

Table 7. Monthly load demand for the high-load house

Month	Flux (kw/m ² /j)	Monthly Consumption (KW)	Normalized array output per unit area (I _m)	Normalized battery bank capacity per unit area (J _m)
January	6.49	2.94	0.18764	0.08384
February	7.124	2.5	0.24222	0.10778
March	7.9120	2.45	0.27450	0.12143
April	7.900	2.39	0.28096	0.13408
May	7.376	2.46	0.25486	0.13303
June	7.2620	2.61	0.23650	0.12929
July	7.3280	2.92	0.21332	0.11469
August	7.370	2.95	0.21236	0.10747
September	7.264	2.82	0.21895	0.10188
October	6.866	2.73	0.21378	0.09621
November	6.342	2.81	0.19184	0.08500
December	6.05	2.92	0.17611	0.08005

Table 8. Results from the simplified method

	Low-load house	Medium-load house	High-load house
Array power (W)	400	600	800
Battery capacity (KWh)	6.82	11.14	14.53
Total number of modules	6.79 : 8	11.37 : 12	14.59 : 16
Number of branches in parallel	3.48 : 4	5.69 : 6	7.26 : 8

Table 9. Results from the LLP method

	Low-Load House	Average-Load House	High-Load House
Imm	0.389	0.235	0.176
Jmm	0.177	0.107	0.08
Aop (m ²)	3.128	5.167	6.921
Cop (kwh)	6.80	11.23	15.04
Pg (w)	323.16	533.71	714.88
Total number of modules	6.45 ~ 8	10.65 ~ 12	14.27 ~ 16
Number of branches in parallel	3.22 ~ 4	5.32 ~ 6	7.13 ~ 8

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