Sizing and management of domestic solar electric installations

N. Tully[1]

(Received January 1999; Final version February 2000)

The performance of a solar photovoltaic system for a domestic installation is predicted using an hourly solar radiation database. A standard procedure is used to estimate the annual average daily solar energy collected by a typical photovoltaic panel, and a system thus sized to to supply a defined average daily energy load with batteries to give between three and five days of energy backup. It is found that this approach gives a system which should provide full service on every day of the year. A matrix of alternative combinations of numbers of panels and storage batteries which can also maintain service is presented, together with indications of the loss of service due to under-designed systems. The possibility of employing a load management strategy to improve the serviceability of a scaled down system is examined, and it is found that an acceptable performance might still be obtained with a 15% reduction in panel area.

Introduction

Solar photovoltaic panels have been quite widely used in South Africa for powering remote communication links. Solar energy is of course a variable resource, not only in the daily sense, but also due to periods of inclement weather, so energy storage is an essential part of a system. In applications of this type, the system sizing has to be such that uninterrupted service is guaranteed, but the relatively high cost of this is justified by the unique solution offered.

An important development in the South African national electrification programme is the expanding application of solar cells for the provision of electricity for domestic purposes in rural or non-grid connected areas. In this application there are alternatives of various sorts, and consumers will also be tempted to compare the costs of their installation with those fortunate enough to be able to have a grid connection. Thus minimising the cost whilst providing acceptable service would be very important.

Domestic solar systems, commonly referred to as solar home systems(SHS), range from a fully electrified home for several inhabitants down to a single 15 W_{peak} panel powering a rechargeable lantern.[1] In general a domestic load is made up of differing components each having their own load schedule. High power applications (space heating, water heating, and normal cooking) are best left to fuel or possibly solar thermal energy, The most common services that are appropriate to solar photovoltaic power are lighting (via compact fluorescent lamps), refrigerators, TV and radio, and microwave cookers, which by virtue of their high efficiency have modest power requirements and low total energy demands. An individual consumer may be tolerant of a reduced level of service on one or more of the loads during periods of low solar insulation and the installation might thus be sealed down and made more affordable either in terms of the number of panels or the number of storage batteries employed .

The purpose of this study was to examine a basic sizing procedure to give uninterrupted service on the worst day of the year, using a database of hourly solar insulation, and to examine whether a worthwhile installation economy can be obtained with a simple load management strategy.

Solar radiation in southern Africa

Global solar insolation comprises direct beam and diffuse components. Data for global and diffuse radiation, measured on a horizontal surface, are available for a number of stations, and these are processed to give the net insolation on tilted surfaces.[2] In solar water heating systems the collectors are usually installed at a slope 10° greater than the local latitude angle in order to maximise the average winter performance. This is generally inappropriate for photovoltaic panels which might ideally be positioned to give their best output on the worst day of the year, but in practice they are usually mounted at the latitude angle. A database is available[3] giving monthly and yearly average solar insolation on surfaces tilted at the local latitude angle. Insolation levels vary widely over different locations and seasons, the best area, represented by data from Keetsmanhoek, having summer insolation levels around 7.9 kWh/m^2/day, whilst Cape Town has a winter level of 4 kWh/m^2/day. Annual average daily insolations range from 7.3 kWh/m^2/day at Keetmanshoek to 5 kWh/m^2/day at Durban.

For the present purpose, hourly data for a typical meteorological year at one of the Pretoria stations is used (Figure 1), having high and low monthly average and annual average insolations of 5.7, 5.3, and 5.5 kWh/m^2/day, respectively.

A function is fitted to the daily variation of the average ambient air temperature for this location.

$$T_{a_0} = 24.2 - 2.625N_d + 3.588N_d^2 - 1.925N_d^3 + .2625N_d^4 \quad (1)$$

where $N_d = D/45.63$ for the first half of the year and $N_d = (365 - D)/45.63$ for the latter half of the year, D being the

[1]School of Mechanical Engineering, University of the Witwatersrand, P.O. Wits, 2050 South Africa

actual day number of the year. The hourly variation on each day is modelled by

$$T_a = T_{a_0} - T_s + (2T_s) * (.508 - .428\cos(h) \\ -.08\cos(2h) + .267\sin(h)) \quad (2)$$

where the daily temperature varies by $\pm T_s$ about the daily average (taken here as $\pm 7^\circ$) and h represents the hour angle.

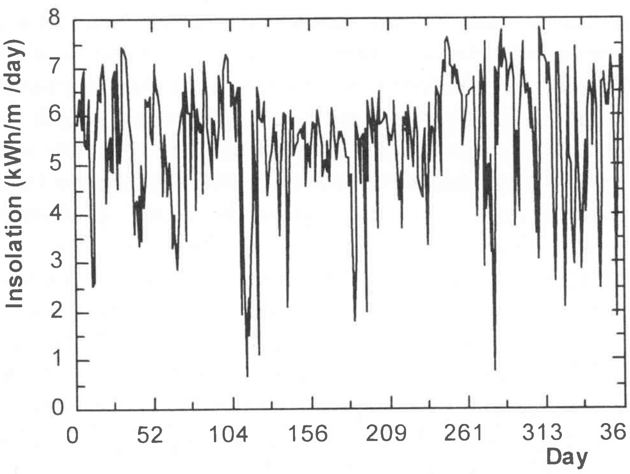

Figure 1 Daily solar insolation for Pretoria

Photovoltaic solar systems

A solar electric system basically comprises solar panels or modules, made up of a number of individual solar cells, connected to a regulator which ideally conditions the power output for maximum gain,[4] and charges a set of d.c. storage batteries. Where 220V a.c. appliances have to be used an inverter is employed.

The PV panel performance is specified by the manufacturer in terms of its nominal power output P_0, its open circuit voltage V_{oc_0} and short circuit current I_{sc_0}, at a reference insolation of 1000 W/m^2 and cell normal operating temperature T_{noc} of 25°C. In operation the short circuit current I_{sc} varies linearly with the insolation (G). The open circuit voltage V_{oc} is affected by the cell operating temperature T_{cell}, which also depends on the insolation level as well as the ambient temperature T_a and by the number of cells in the panel N_{cell}. A 'fill factor' F is defined, which is the nominal power divided by the product of the reference condition open circuit voltage and short circuit current. The fill factor is assumed to be approximately constant.

The relationships used are[3]

$$I_{sc} = I_{sc_0} \times G/1000 \quad (3)$$

$$V_{oc} = V_{oc_0} - 0.0023 \times N_{cell} \times (T_{cell} - 25) \quad (4)$$

where $T_{cell} = T_a + (T_{noc} - 20) \times G/800$

The actual power output is

$$P = I_{sc} \times V_{oc} \times F \quad (5)$$

System sizing

The sizing of a system basically requires the delivery by the solar cell panels of sufficient total energy to meet the average daily load, and the provision of sufficient storage capacity not only to cover night-time operation of domestic loads, but also to meet a desired autonomy over periods of overcast weather.

The energy that a single panel can deliver in kWh/day is estimated by dividing the average daily insolation energy in kWh/m^2/day (obtained from Eberhard[3] or a similar data bank, interpolating between weather stations if necessary), by the reference insolation level ($G_0 = 1$ kW/m^2), and multiplying by the rated power of the panel P_0 in watts.

The number of panels required is determined by estimating the annual average daily domestic loads. Standard practice[5] is to increase the d.c. loads by 30% and the a.c. loads by 40% to allow for system losses. The storage capacity is determined from the average (taily energy load, increased by 30%, multiplied by the number of days autonomy required.

Basic system performance

A domestic system which has a 12 V d.c. fridge/freezer, four 18 W d.c. compact fluorescent lamps, a 45 W a.c. television/radio, and a 500 W a.c. microwave oven is considered. It is assumed that the lights are used from sunset to 22h00, the television from 18h00 to 22h00, and the microwave cooker for 10 minutes at 08h00, 20 minutes at 12h00, and 10 minutes at 18h00. The refrigerator is assumed to use a variable averaged power depending on the ambient temperature, according to an approximate function $(50 + 10 \times (T_a - 25)/5)$ W. This gives an annual average daily load on the system of 2.50 kWh/day.

The solar panels are assumed to be located at Pretoria and to be fixed at a slope equal to the latitude angle and to face North. The basic sizing procedure gives a total rated panel power requirement of 455 W, here taken as thirteen 35 W panels, and initially ten 120 Ah 12 V batteries are specified providing a $4\frac{1}{2}$ days reserve.

The net energy delivered to or from the storage batteries is calculated every 15 minutes on each day of the year. When the batteries are fully charged, excess energy is discarded. The performance of the system is evaluated in terms of the residual energy stored in the batteries at midnight. Figure 2 shows the residual for each day of the year. It is seen that the specified design always provides full service according to the above definition, although this would not necessarily mean that the refrigerator gets power between midnight and sunrise or that the microwave oven can be used at 08h00.

Effect of panel area and storage capacity

It would seem logical to suppose that more solar panels and fewer batteries, or vice-versa, could also service the demand. Whilst investigating combinations of panels and batteries it is also useful to consider the effect of undersizing the system. This is done by finding the number of days in the year on which the batteries are depleted by midnight. This concept is expanded to a further criterion which identifies the number of occasions on which the system is exhausted at midnight on two consecutive days and on three consecutive days. Two or three such 3-day periods might be the limit of acceptability by most consumers, although it must be noted that there is always collection of diffuse radiation on overcast days, and also that a refrigerator has its own thermal energy storage capacity, so service is not totally lost.

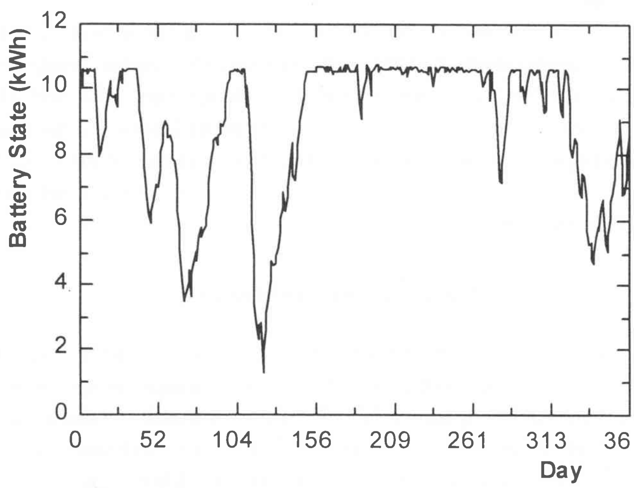

Figure 2 State of the batteries at midnight

The findings are presented in a matrix in Table 1, where the set of three numbers represent the 1-day, 2-day, and 3-day failures, respectively (NB: a sequence 6/3/2 would imply a continuous 6-day period). It is seen that the $4\frac{1}{2}$ days reserve initially specified is longer than necessary for Pretoria — 31 days or eight batteries would maintain full service. It is also seen that serviceability is more critically dependent on the number of solar panels than the number of batteries. A general trend is seen between the numbers of panels and batteries which will give various levels of service, but as the cost ratio between 35 W panels and 120 Ah batteries is around 4 to 1, saving panels by increasing the number of batteries would not normally be an attractive option.

It is worth noting that the days on which service is lost are mostly overcast, so beam radiation is small or nonexistent and the direction the panel faces is not likely to be important. Performance calculations with panel slopes 10° above and below the latitude angle, and azimuth angles ±45° from North confirm that in terms of the present criteria the orientation of the panels has little effect.

The effect of load shedding

In the interests of minimising the cost of the initial installation, but retaining some control over the effects of insufficient energy delivery, a conscious load shedding strategy might be invoked. One possible approach would be to monitor the state of the batteries and when the energy reserve has declined to certain levels, to disable the microwave oven — assumed to be the least important load — the TV, and then the lights, in that order, leaving the refrigerator connected. An example is shown where the number of panels has been reduced from 13 to 11 (a 15 % reduction), but 8 storage batteries retained. Without control there are 21 occasions on which the system is depleted at midnight for three consecutive days. If the three services above are disabled when the battery capacity has fallen to 1.25 kWh, 750 Wh, and 300 Wh, respectively, the 3-day depletions are reduced to two occurrences. The availability of the different services is depicted by the white areas in Figure 3. The oven would not be available on 37% of the mornings of the year (bottom black band), but could mostly be used in the evening (top white band). Total loss of lighting would occur on 9 days in the year, but since there is always collection of diffuse radiation, the refrigerator would never lose power completely.

Discussion and conclusion

The use of a typical year solar radiation database can only give an expectation of the average performance of a solar photovoltaic system over a number of years. It does however serve to emphasise that system sizing depends on the required performance for a few bad solar days in the year. This further suggests that since these days have little or no beam radiation component, panel orientation is not critical. The results obtained suggest that for locations with similar insolation patterns to the Pretoria area, the basic

Table 1 Number of one, two, and three day failures with various panel/battery combinations

	Peak watts	385	420	455	490	560	700
	No. of panels	11	12	13	14	16	20
No. of batteries	Days reserve						
1	.45						12/4/2
2	.9						3/2/1
4	1.8			11/6/3	4/2/1	2/1/0	0/0/0
6	2.7			3/1/0	1/0/0	0/0/0	
8	3.6	52/32/21	10/6/4	0/0/0			
10	4.5		7/3/2	0/0/0			
15	6.75	38/21/12	0/0/0				
20	9	0/0/0					

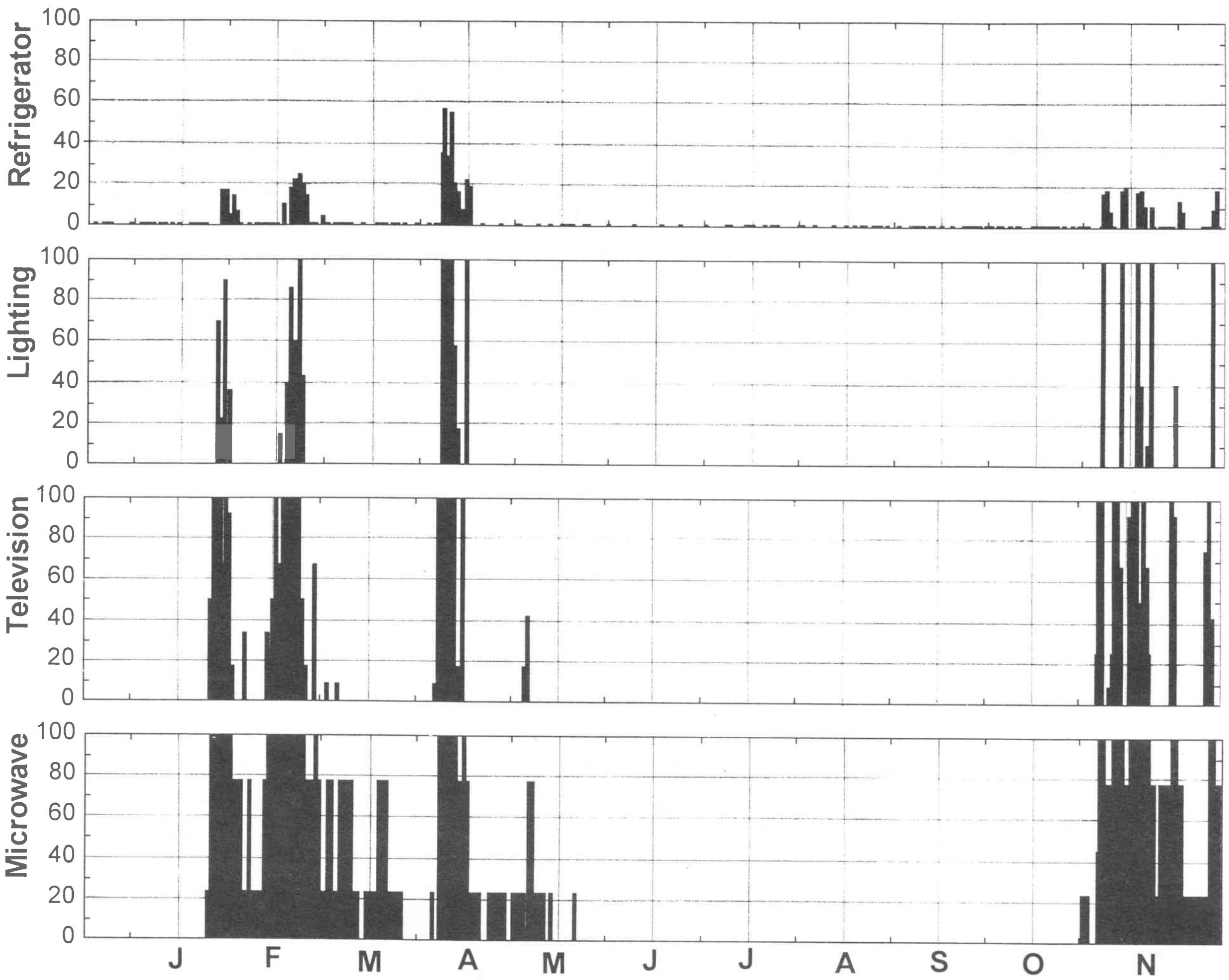

Figure 3 Availability of the services with load management

sizing procedure used gives the correct number of solar panels to provide continuous service, and that four days back-up battery storage would be ample. It is anticipated that coastal areas would require more storage capacity, and system design should possibly be based on the lowest monthly daily average insolation rather than the annual average.

An examination of possible system configurations shows a general trend in which increasing the number of storage batteries allows a reduction in the number of solar panels, although with the present cost structure there would be no advantage in this course of action. Undersizing the system to reduce initial cost leads to periods when insufficient energy is available from the system, although this can be mitigated by a load shedding strategy to ensure that essential needs are met. The approach examined here of monitoring the status of the storage and beginning to shed load when around half a day's energy remains would not, however, appear to allow much more than a 15% reduction in the number of panels.

References

1. I.T. Power. *Electricity from sunlight.* Department of International Development, London, 1997.

2. Lunde P.J. *Solar Thermal Engineering.* Wiley, New York, 1980.

3. Eberhard A.A. *A solar radiation handbook for Southern Africa.* E.R.I., Cape Town, 1990.

4. Markvart T (ed.). *Solar Electricity.* UNESCO Energy Engineering Series, Wiley, 1995.

5. Photovoltaic Worldwide: Siemens Solar Products catalogue. *Siemens Solar*, 1996.