How large battery is needed to turn a solar cell into a useful power supply ?

Tom Markvart
School of Engineering Sciences, University of Southampton, Southampton SO17 1BJ, UK

The fluctuating nature of solar radiation remains one the most series obstacles for a wider use of solar electricity. The problem is often viewed as the need to shift the mid-day energy supply peak towards the evening peak of demand. In reality, a deeper analysis is needed based on the statistics of solar radiation (see e.g. references [1] – [6] for a background to this field). This paper illustrates the key principles involved on the example of finding the array and battery sizes for stand alone PV systems.

A simple argument based on daily energy balance [1] is often used to determine the PV array P_o needed to supply daily load L:

$$P_o = \frac{L}{\langle G \rangle} \tag{1}$$

where $\langle G \rangle$ is the long-term average solar daily radiation, often referred to as the Peak Solar Hours. The simplest design guidelines then recommend a battery size to accompany the array (1) determined by a rule of thumb ("by experience") simply from the latitude of the site [1].

More accurate sizing procedures consider the array and battery together as a pair of variables (C_A, C_S) which define the configuration of a stand-alone PV system. In a dimensionless form,

$$P_o = C_A \frac{L}{\langle G \rangle} \quad ; \quad C_S = \frac{B}{L} \tag{2}$$

where C_S is usually called the Days of Autonomy.

The sizing method discussed in this paper determines the configuration that will supply power to a load with a required reliability of supply by analysing the key intervals with low solar radiation called *climatic cycles* (Fig. 1). To maintain a continuous electricity supply to the load during the cycle, the required battery size B, in energy units, must satisfy

$$B \geq n_c (L - P_o \langle G \rangle_{cc}) \tag{3}$$

or

$$\frac{1}{n_c} C_S + \frac{\langle G \rangle_{cc}}{\langle G \rangle} C_A \geq 1 \tag{4}$$

The relevant system configurations that satisfy (4) can be depicted in a particularly clear way in a plane where they are represented by points with coordinates (C_S, C_A) (Fig. 2).

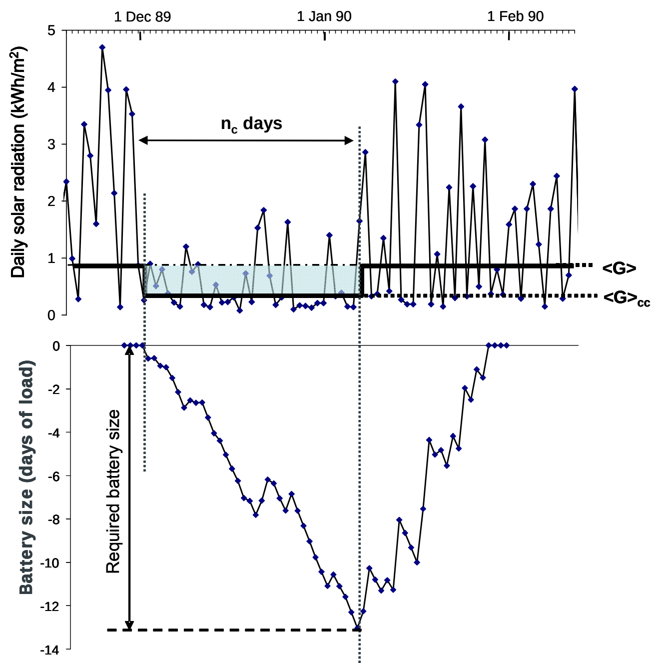

Fig. 1. A climatic cycle of n_c days with an average daily solar radiation $\langle G \rangle_{cc}$, below the long-term average $\langle G \rangle_{cc}$

This formalism can easily be extended to analyse a period of time with several climatic cycles. Figure 3 shows the resulting construction for the South of England during 1989-1990 based on the data [7]. The shaded area describes systems which would deliver uninterrupted power to the load during the period in question – in this case, during the years 1980 – 1990.

The method outlined here (described in more detail in [8]) is based on a definition to supply reliability which is close to the established engineering practice (used, for example, to asses the effect of extreme winds on building structures or in the design of flood protection measures [9]) where extreme values are considered as functions of certain recurrence intervals.

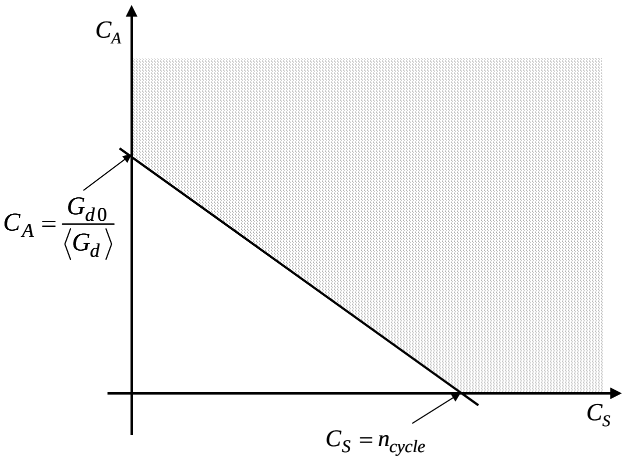

Fig. 2. A graphical method of solution for equation (4). System configurations that comply with (4) lie in the shaded area of the plane.

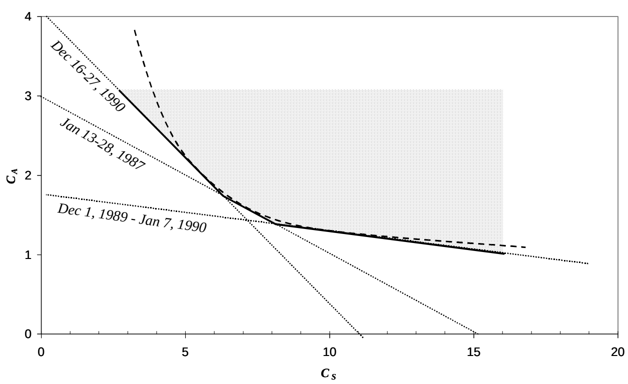

Fig. 3. The sizing curve obtained by combining the lines corresponding to three most prominent climatic cycles during the 1980-90 decade

In a simplified form where the array size is set at a constant multiple of P_o (2), the required Days of Autonomy can be determined from a simple system model and displayed graphically to indicate the likely reliability of supply (Fig. 3), and has been used to determine the required number of the Days of Autonomy (DoA) for solar vaccine refrigeration systems in the tropics, providing a standard for the World Health Organisation [10] (Fig. 5).

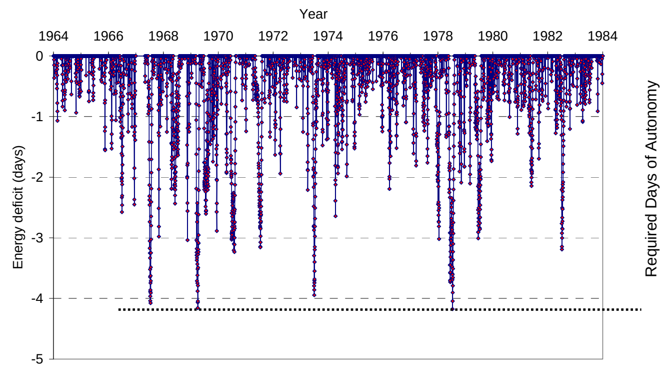

Fig. 4. The energy deficit for Bulawayo, Zimbabwe, illustrating the determination of DoA with supply reliability of some 20 years. Each point represents the energy deficit at the end of one day.

References

[1] S. Silvestre, Review of system design and sizing tools, in T. Markvart and L. Castañer (eds), *Practical Handbook of Photovoltaics: Fundamentals and Applications*, Elsevier, Oxford (2003).

[2] J.M. Gordon, Optimal sizing of stand-alone photovoltaic solar power systems, *Solar Cells* **20**, 295 (1987).

[3] M.A. Egido and E. Lorenzo, Review of sizing and a proposed new method, *Solar Energy Materials and Solar Cells* **26**, 51 (1992)

[4] E. Lorenzo *et al*, *Solar Electricity: Engineering of Photovoltaic Systems*, Progensa, 1994.

[5] L.L. Bucciarelli, Estimating loss-of-power probabilities of stand-alone photovoltaic energy systems, *Solar Energy* **32**, 205 (1984)

[6] L.L.Bucciarelli, The effect of day-to-day correlation in solar radiation on the probability of loss-of-power in a stand-alone photovoltaic energy system, *Solar Energy* **36**, 11 (1986)

[7] K. Scharmer and J. Grief (co-ordinators) *European Solar Radiation Atlas*, 4th Edition, Les Presses de l' École des Mines, Paris (2000).

[8] T. Markvart, A. Fragaki and J.N. Ross, PV system sizing using observed time series of solar radiation, *Solar Energy* **80**, 46 (2006)

[9] E. Castillo, *Extreme Value Theory in Engineering*, Academic Press, London/ San Diego (1988)

[10] T. Markvart and H. Toma, Solar power system for vaccine refrigerators, World Health Organization Report WHO/PQS/E003/PV01-VP1.2 (2008).

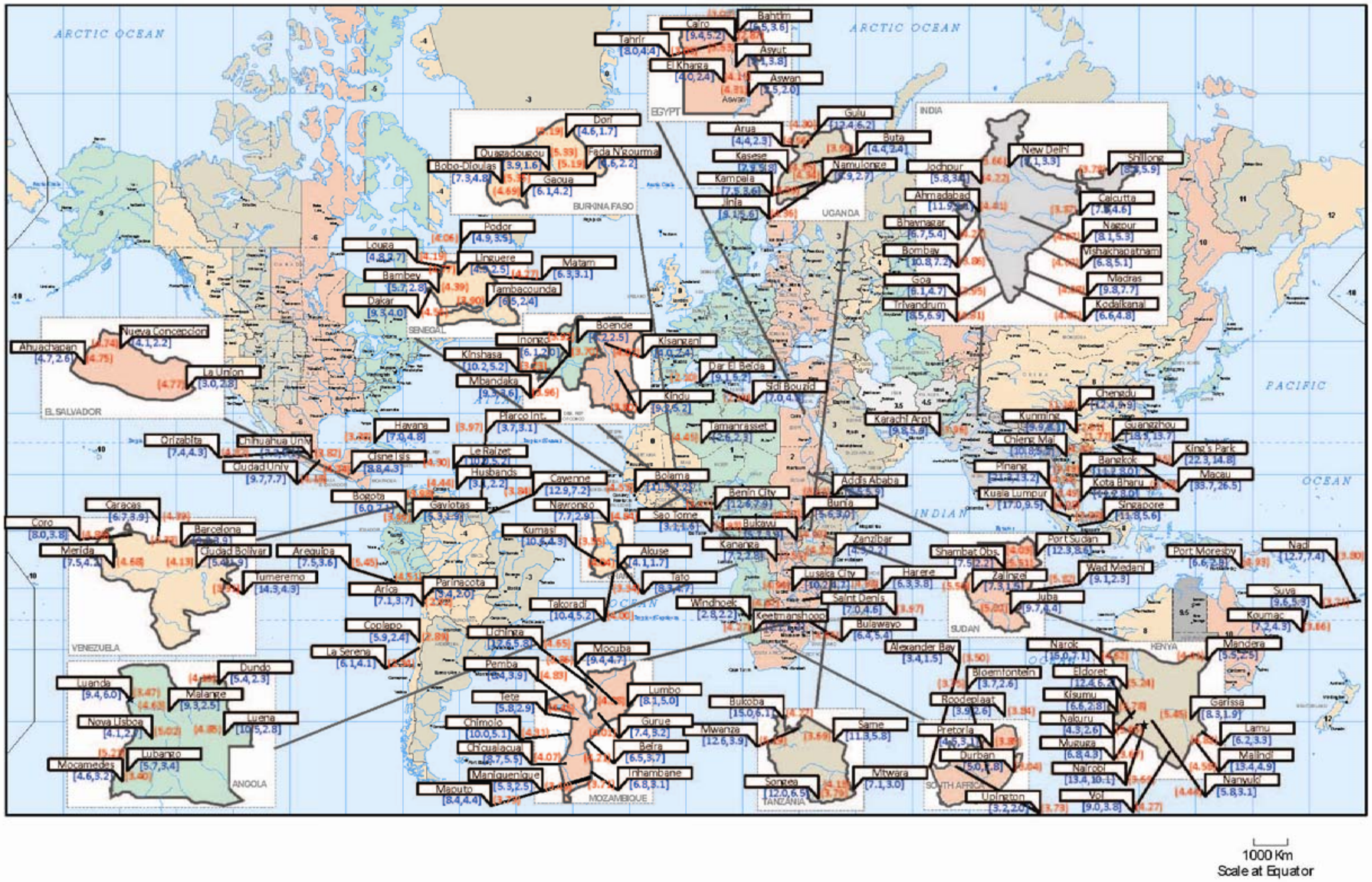

Figure 5 Days of Autonomy for World Heath Organisation solar vaccine refrigeration systems, determined for 200 locations in the tropics. The red numbers give the design solar radiation during the "worst month" of the year; the two blue figures show DoA values for an array given by (1) and for an array oversized by 20%.