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How to build a photovoltaic system

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This paper gives an overview of photovoltaic system engineering. Several issues are discussed that are currently under consideration in the area of grid-connected and stand-alone systems. The regulatory framework for the utility interface of a photovoltaic system is outlined, with examples of criteria which usually need to be satisfied by a grid-connected system before connection to the utility network is permitted. An area that has received considerable attention in the design of stand-alone systems is sizing. Several sizing methods are discussed, and a possible extension of one of the sizing techniques to photovoltaic/wind energy hybrids is also briefly discussed.

Keywords: photovoltaic system, grid-connected and stand-alone systems, sizing methods.

1. Introduction

In the half century since development of the first modern solar cell, photovoltaic systems have been used in a variety of applications, spanning power capabilities of more than six orders in magnitude. Small systems of several watts in size that were used to supply electricity to satellites in the late 1950s were followed by remote industrial systems for professional applications on the ground and power supplies for small consumer appliances. Today, photovoltaic power systems for water pumping, lighting and other applications are bringing substantial social benefits to the developing countries. In many industrial countries, grid-connected systems are being installed as part of utility-scale distributed electricity generation (Fig. 1). Clearly, system engineering plays an important role in the construction of a satisfactory solar electricity supply.

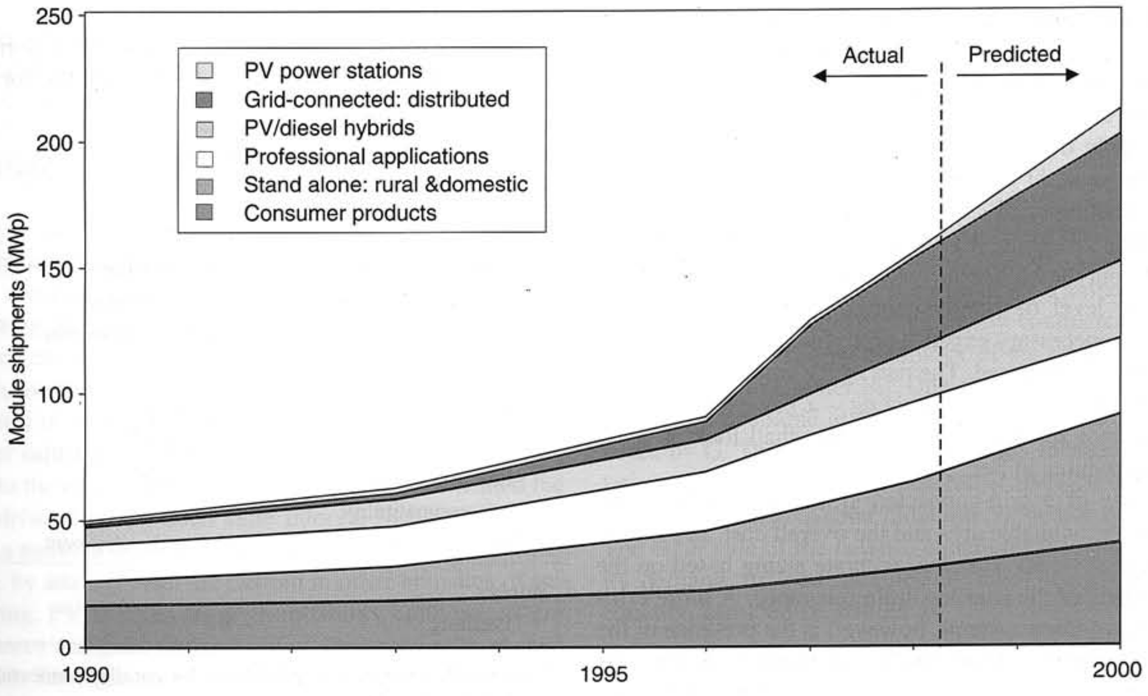

Fig. 1. The markets for photovoltaic systems (after Ref. 1).

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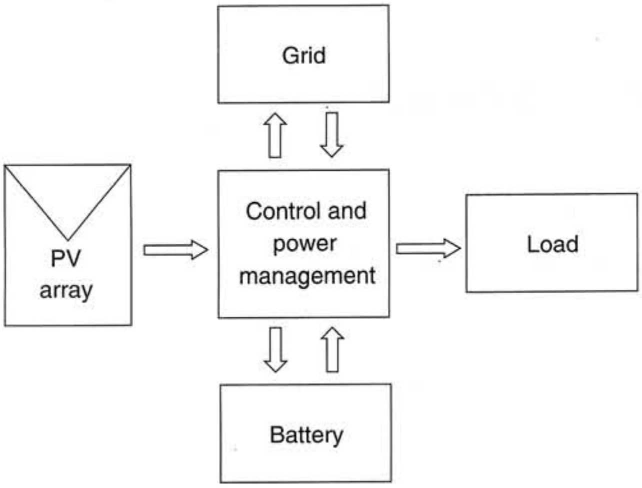

Fig. 2. Schematic diagram of a photovoltaic system.

A schematic diagram of a photovoltaic system is shown in Fig. 2. This figure does not include hybrid systems or systems with a diesel back-up. Stand-alone photovoltaic systems (with the possible exception of systems used for water pumping) usually include energy storage in the form of lead acid batteries. Some form of battery charge management is then normally contained in the control subsystem. Batteries are usually omitted from grid connected systems. Inverter is necessary if AC power is required, either locally or to be exported to the utility distribution (the "grid"). In the latter case, the inverter will also need to contain a suitable utility interface.

The simplicity of Fig. 2 is somewhat superficial, and conceals significant differences between stand-alone and grid connected systems that affect their fundamental design. As the name implies, stand-alone systems are used where no utility supply is available, and two considerations are paramount in their design. Firstly, solar cells and batteries are not cheap, and the user will normally wish the system to supply the maximum amount of power at the right time of the year. At the same time, no system can guarantee absolute continuity of supply because of the statistical nature of solar radiation. The large the system, the better the reliability but the higher the cost. The user should therefore design the level of supply continuity that is needed, to avoid the unnecessary expense of a system that is too large for the services required. The part of PV system design that deals with these questions is sizing – a key exercise when constructing a stand-alone system. We shall look at some sizing procedures in Sec. 3.

The size of a grid-connected system is usually determined by the available area and the overall cost. In contrast with stand alone PV systems, accurate sizing based on the energy needs of the user has little relevance. A more critical feature of these systems, however, is the presence of the utility distribution. This usually guarantees, on the one hand, that sufficient energy is available in times of low solar radiation and, on the other hand, that excess energy not consumed by the local user can be exported to the utility – sometimes for economic benefit to the owner of the PV system. What is not always appreciated is the fact that a connection to the utility which allows export of power (usually called synchronous connection by the power engineers) entails conditions on the inverter and on the interface between the inverter and the utility network. We shall look at grid connected systems in more detail in Sec. 2.

2. Grid-connected systems

Before focusing on synchronously connected systems – the most common types of grid connected PV systems today – it is worthwhile mentioning that this is not the only type of system which can be connected to the "grid" (Fig. 3). We would like to draw attention not only to the structure of these systems but also their nomenclature which is by no means standardised, and different names are usually used by the electricity industry personnel and the PV community. In situations where power produced by the PV system is always less than the local load, for example, a PV system with 'grid backup', will give the user a high reliability of supply without the onerous nature of having to comply with the utility regulations.

Permission from the local distribution network operator (DNO) normally has to be obtained for synchronously connected systems since the DNO is obliged to protect the integrity of the system and of all of the consumers connected to it. The utility requirements on the inverter will usually cover the areas of safety of personnel, protection of equipment, and the power quality. Guidelines and regulations are being developed in a number of countries specifically for small PV systems. An example of inverter tests which are usually requested by the utility in the UK before connection is permitted are shown in Table 1.

Most of these tests are covered by existing norms and standards. Many countries have similar criteria, for exam-

Function	Reference
Protection	
General	IEC 255
Under/over voltage	UK Guidelines[1]
Under/over frequency	UK Guidelines[1]
Loss of mains	Under development
Supply quality	
Harmonics	BS & EN[2]
Voltage flicker	BS & EN[2]
Electromagnetic compatibility	BS & EN[2]
DC injection	Under development
Safety	
Earthing	BS[3]

[1] Covered by existing UK guidelines for parallel connection of embedded generators

[2] Covered by existing British standard and European norm

[3] Covered by existing British standard

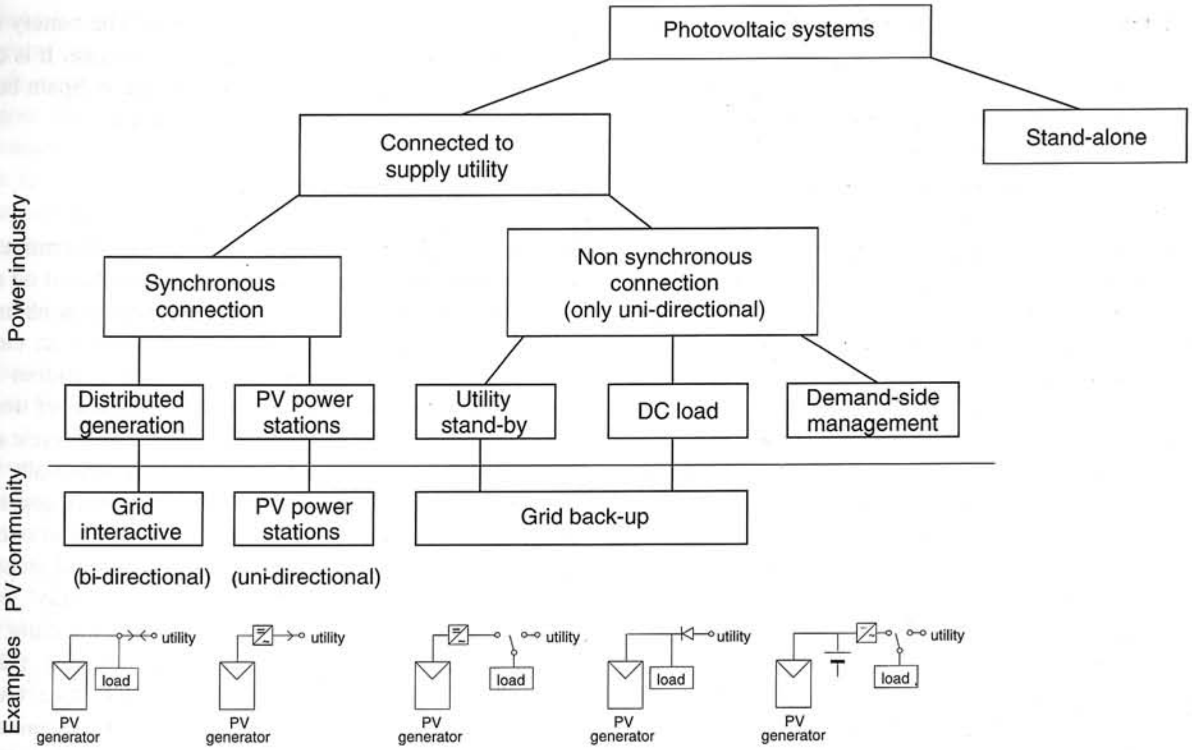

Fig. 3. There is more than one way of connecting a PV system to the 'grid' – and different names for the interconnection.

ple, on the limits of harmonics and DC injection allowed by a generator. The loss of mains test, however, is likely to be more stringent than normally required since, in the future, there may be a number of small PV systems connected to one utility supply line. This enhances the probability of island operation and the protection equipment must therefore be able to detect the absence of mains even in this situation. Most PV inverters for grid-connected systems therefore contain anti-islanding protection which may be integral to the inverter operation – unlike the protection relay of conventional rotating generators.

3. Sizing of stand-alone systems

Sizing of stand alone systems represents an important step in their design. Since the capital equipment represents the major component in the price of photovoltaic electricity, oversizing the plant has a very detrimental effect on the price of the generated power. Undersizing a stand-alone system, on the other hand, reduces the supply reliability. The level of supply reliability is sometimes expressed as a number called loss-of-load probability, abbreviated to LLP, equal to the estimated time that the PV system will shed the load, divided by the total time interval in question. It is worth a mention that other criteria can also be used. For example, by analogy with the custom in other branches of engineering, PV systems for high-reliability applications are sometimes designed on the basis of the time series of data available for a given location. One can then specify that a system has been designed to operate without shedding load for 25 years, say.

A variety of sizing procedures exist, and it is only possible to give an short illustration of how the sizing problem has been approached (see, for example, Refs. 2 and 3 for a comprehensive review of the field). The sizing method based on energy balance provides a popular technique, and we shall also show how this method can be modified to size photovoltaic-wind hybrid systems. The random walk method of sizing is probably more academic in nature but it does illustrate how the reliability of supply can be introduced. A brief mention will also be given of a more sophisticated method which allows accurate sizing in a more realistic situation.

3.1. Sizing based on energy balance

Sizing based on energy balance is probably the simplest of the sizing techniques but, because of its transparency, it is widely used in a variety of guises by commercial PV system companies. The methodology of the method presented below is due to Castaer [4]. One starts with the average solar energy available at a given location which will be denoted by G. This should be the monthly means of daily solar energy at the inclined panel, rather than the meteorological data which give solar radiation on the horizontal plane. The other side of the balance equation is the daily electricity demand, or load (denoted by L). The energy balance equation can then be written as

$$\langle G \rangle_y A = L \qquad (1)$$

where $\langle \ldots \rangle_y$ indicates yearly average and A denotes the array size. The daily solar radiation G, if expressed in kWh/m^2, is commonly referred to as peak solar hours (PSH). Thus, the meaning of Eq. (1) is that the average available energy (number of hours of the peak solar radiation multiplied by the array in W_p, say) must be equal to the daily load in Wh. The battery size can then be calculated from the charge deficit needed to store the energy generated in summer to be used during the winter months (Fig. 4). This is the seasonal charge deficit. A further energy storage is usually added to supplement this design charge deficit to cover periods when the actual solar radiation is below the average values over an extended duration of time. In most locations in temperate climates, the storage of solar energy from summer to winter is not a viable proposition as it results in an enormous battery size. The solution is either to connect a small wind turbine to cover the energy demand in winter (see Sec. 3.3) or to increase the size of the array to reduce the charge deficit. The different array sizes can then be plotted as a function of storage to determine the optimal (least cost) system (Fig. 5).

With seasonal charge deficit, these methods are usually suitable for low-reliability domestic systems where the user can adapt energy demand according to the actual energy available. In high-reliability professional applications, the array is usually chosen so that it can cover the demand during the 'worst month' of solar radiation. The battery size, however, can only be determined by experience. It is common to use, for example, 5 days of storage in Spain but 15 or more days are usually required in the UK.

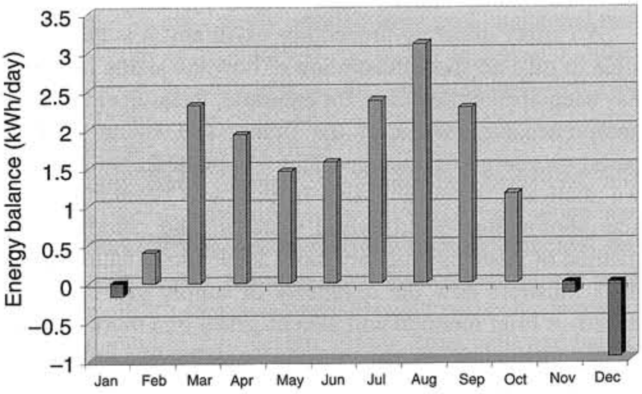

Fig. 4. The seasonal charge deficit.

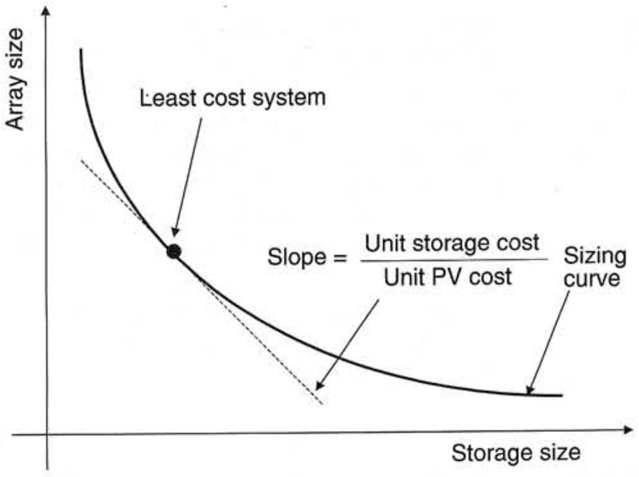

Fig. 5. The "sizing curve".

3.2. The random walk method

The sizing method based on energy balance determines the relationship between array and battery sizes based on average meteorological data but gives no indication about the reliability of supply. Bucciarelli [4] pioneered an elegant method of sizing based on the method of random walk which makes this possible. The method consists of treating the possible states of charge of the battery as discrete numbers, to be then identified as sites for a random walk. Each day, the system makes a step in the ransom walk depending on solar radiation: one step up if it is 'sunny' and one step down if it is "cloudy". The magnitudes of these steps and probabilities of weather being 'sunny' and 'cloudy' are determined from the solar radiation data and the daily load. When the random walker resides in the top state, the battery is fully charged; when it is in the bottom state, the battery is completely discharged and the load is disconnected. The calculations are carried out by assuming that, after a certain time, the random walker reaches a steady state. The loss of load probability is then equated to the probability of the random walker residing in the lowest state (Fig. 6). Bucciarelli [5] subsequently extended this method to allow for correlation between solar radiation on different days.

3.3. Other methods

The sizing method based on energy balance and the random walk method are only two possible methods of sizing. Among the multitude of more complex techniques, one should mention the method of Egido and Lorenzo [3] who have devised a way of representing the sizing curves for

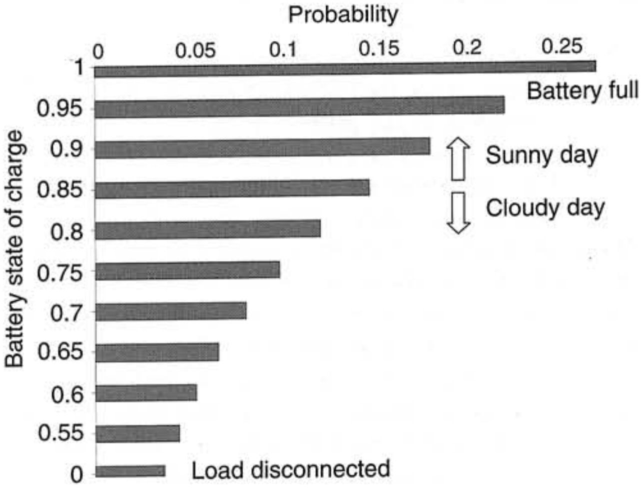

Fig. 6. The site occupation probabilities in random walk method of sizing. In this particular case, 0.5 is the minimum state of charge to which battery is allowed to be discharged.

each LLP using a small number of parameters. These parameters can then be calculated from observed (or synthesised) meteorological data and each parameter plotted as a contour map. Egido and Lorenzo have used this procedure to constructed a "sizing map" of Spain which makes it possible to design easily a photovoltaic system for any given location which will deliver energy with a desired reliability of supply.

3.4. Sizing of hybrid PV/wind energy systems

In locations with large seasonal variation of solar radiation where wind energy may also form an important resource (Fig. 7), it may be more cost effective to install a hybrid PV/wind energy system rather than just a PV system alone. A method described below – which is also based on energy balance – can help us decide when this is the case. Although this method is only suitable for locations where wind is reasonably reliable (for example, near the coast), it provides a simple criterion to indicate which of the three alternatives (PV or wind only or a combination of the two) is the most suitable solution. The method presented below is based on a simple summer-winter argument but a full monthly analysis can be developed in a similar manner [7].

Let us denote the daily solar and wind energy values for the site in question for a typical summer and winter day by solar(summer), solar(winter), wind(summer) and wind (winter). The average daily wind energy can be calculated from the average wind speed v using the expression

$$\frac{D}{2}\rho_{air}\langle v^3\rangle_D \tag{2}$$

where ρ_{air} is the density of air (usually taken as 1.22 kg/m^3), D is the duration of one day (24 h), and the brackets $\langle\ldots\rangle_D$ denote the daily average. One would usually verify the energy supplied by the two generators (wind and solar) by modelling when the characteristics of the wind turbine are known. Typical data for the south of England are shown in Fig. 7. It is seen that the solar and wind energy are, to a good degree, complementary. We shall see below that this usually provides a justification for installing a hybrid system.

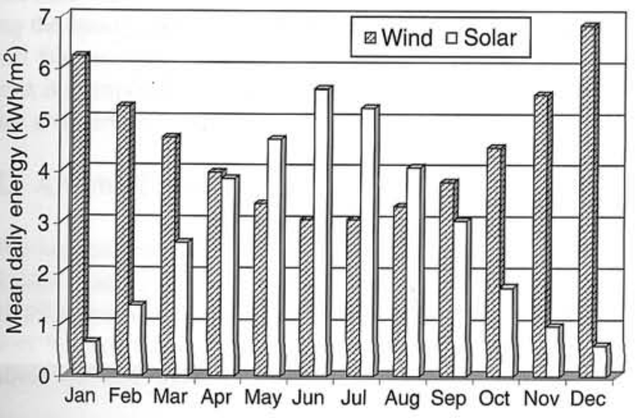

Fig. 7. Solar and wind energy resources in the south of England.

If the daily energy demand is d(summer) and d(winter), the sizes PV and WT (in peak or rated power units) of the two generators must be such that the energy delivered by the generating systems exceeds the load

$$\begin{aligned}&\mathrm{PV}\times \mathrm{solar(summer)} + \mathrm{WT}\times \mathrm{wind(summer)} \geq \mathrm{d(summer)}\\ &\mathrm{PV}\times \mathrm{solar(winter)} + \mathrm{WT}\times \mathrm{wind(winter)} \geq \mathrm{d(winter)}\end{aligned} \tag{3}$$

Equation (3) assumes that the battery acts simply to average out deviations from the average solar and wind energy values; no seasonal storage is here envisaged.

The solution of Eq. (3) is conveniently carried out by a graphical construction in the (PV, WT) plane where each point represents a combination of PV array and wind turbine sizes. The solution of the equation

$$\mathrm{A}\times\mathrm{PV} + \mathrm{B}\times\mathrm{WT} \geq \mathrm{C} \tag{4}$$

where A, B and C are constants then corresponds to a half-plane bounded by a line whose equation is given by (4), with the ≥ sign replaced by =. The solution of (3) is then represented by the intersection of two such regions, as shown in Fig. 8.

The optimum (least cost) solution lies in one of the three vertices of the shaded region. Two of these points represent PV array and wind turbine; the third point represents the hybrid. The costs of these three alternatives can then be easily compared. For example, for south of England the hybrid solution usually comes out to be most effective for small systems in the region up to about 1 kW. We should emphasize, as already mentioned, that this procedure is only valid is locations where wind energy represents a reasonably "reliable" resource in the sense that the actual daily values are close to the average. Otherwise, a very large battery would be needed which would offset any advantages gained from installing the hybrid.

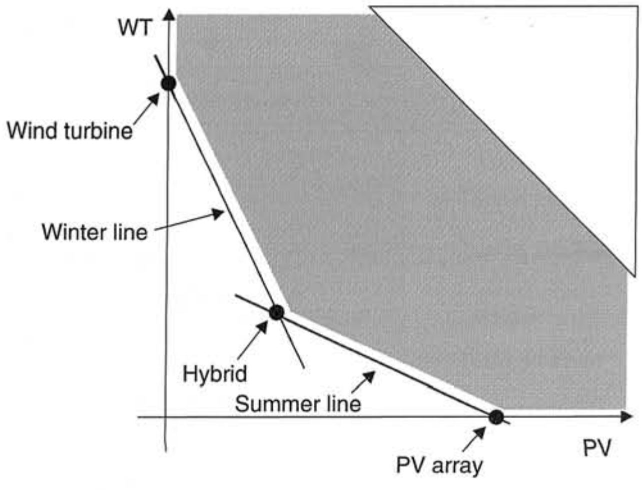

Fig. 8. The optimum configurations of a PV/wind hybrid (points). The shaded region indicates solutions of Eq. (3).

A similar graphical procedure can be used if a more accurate solution based on monthly values is required. In the limit of short time intervals, the vertices of the feasibility region then become a smooth line similar to the sizing curve of Sec. 3.1, and a similar technique can then be used to find the optimum system.

4. Conclusions

Differences between the two types of photovoltaic systems, grid-connected and stand-alone, have been discussed. We have shown that whilst the design of stand-alone systems focuses on the desire to use the maxium amount energy from the resource at the maximum reliability of supply, the design of grid connected system emphasises safety, protection and power quality. An example of the likely tests than might be demanded for an inverter in grid-connected systems has been discussed. The design of stand alone systems, in contrast, centres around a good sizing procedure, and four types of sizing procedures have been discussed. A method based on energy balance, suitable for stand-alone systems where low cost represents a higher priority than the reliability of supply, Bucciarelli's random walk method, and the method of Egido and Lorenzo. In central and northern Europe with large seasonal variations of solar radiation, a hybrid PV/wind energy system may represent a cost effective alternative, and a possible sizing procedure for these systems has also been discussed.

Acknowledgements

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