REVIEW AND RECOMMENDATIONS FOR IMPROVING THE MODELLING OF BUILDING INTEGRATED PHOTOVOLTAIC SYSTEMS

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ABSTRACT

The models for photovoltaic (PV) systems currently in ESP-r prove very useful in estimating the electrical and thermal impact of building-integrated photovoltaics. However, while they represent well the impact of photovoltaics on the building's thermal energy balance, they may lack in accuracy in the prediction of the system's energy production. To achieve both goals at once it is suggested to improve the PV models in ESP-r, taking into account all phenomena affecting the power output of PV modules: solar radiation intensity, cell temperature, angle of incidence, spectral distribution, uncertainty in manufacturer's ratings, ageing, mismatch, soil and dirt, snow, partial shading, diodes and wiring. This would provide a more realistic estimate of the probable output of the PV system over its lifetime. It is suggested to implement three models: a simple model based on constant efficiency, a one-diode equivalent model with explicit temperature dependency of the parameters, and the Sandia model for cases when detailed modeling is required.

INTRODUCTION

Modeling building-integrated photovoltaics (PV) in building energy simulation tools presents many challenges. For example, photovoltaics respond to many environmental influences, such as irradiance, temperature, wind speed, angle of incidence of solar rays, and spectral distribution of irradiance. Furthermore, PV modules are susceptible to hard-to-quantify effects such as the presence of snow or dirt, and shading from one part of the building onto the module.

In addition, parameters characterizing PV modules are often hard to come by. Manufacturer's data often provide relatively easy access to parameters such as open circuit voltage, short circuit current, and nominal efficiency under standard test conditions (1000 W/m^2, 25 °C, air mass 1.5). But representing accurately the electrical characteristics of the modules from such a small set of parameters, and under a wide range of environmental conditions, is challenging.

Finally, most PV simulations programs are chiefly interested in the power output of the module. By contrast, tools for energy simulation in buildings require additional outputs such as light reflected by the modules and transmitted through it, and radiative, convective and conductive heat transfer at the front and the back of the PV array.

This paper examines the various environmental effects affecting the behaviour of PV modules, and quantifies their importance upon the calculation of energy delivered by the PV array on an hourly, monthly and yearly basis. It reviews the PV models currently used in ESP-r, and describes its strengths and weaknesses. Finally the paper proposes a more complete PV model for building integrated photovoltaics in ESP-r.

PHOTOVOLTAICS: BACKGROUND

Photovoltaic modules convert sunlight into electrical power. Several kinds of modules are commercially available: crystalline silicon (c-Si), which can be either monocrystalline silicon (mono-Si) or polycrystalline silicon (poly-Si), and amorphous silicon (a-Si). Other more exotic technologies such as spheral silicon or Cadmium Indium Selenide (CIS) are also available, although their commercial impact is so far limited.

The modules differ chiefly by their efficiency, their packaging, and their cost. Different technologies respond also differently to environmental stimuli such as temperature, spectral conditions, etc.

From an electrical point of view, PV modules are characterized by their current vs. voltage curve, commonly called I-V curve, some examples of which are shown in Figure 1. The power delivered by the module is the product of its voltage and current, so one has to know the operating point (i.e. voltage and current) of the module to determine the energy produced. In some systems the operating point is determined externally, for example in the case of a direct connection to a battery. In that case, the voltage is basically set to the battery voltage (e.g. 12 V) and the PV module current is determined by the intersection of the I-V curve with the 12 V vertical line. In most building-integrated PV systems, though, an electronic device called a maximum power point tracker adjusts the voltage so as to maximize the power delivered by the module. In that case the module operates near the 'bend' in the I-V curve.

As shown in Figure 1 the shape of the I-V curve depends on irradiance and temperature; very roughly, irradiance is a first-order effect and temperature is a second order effect. There are other influences as well, such as angle-of-incidence, spectral distribution of irradiance, etc., which also change the shape of the I-V curve; these will be described later in the paper.

Modules are usually not used alone. Photovoltaic systems usually include power conditioning equipment, inverters, and in some cases batteries (for stand-alone systems). All these additional components constitute what is called the balance of system (BOS) and will be briefly touched upon at the end of this paper.

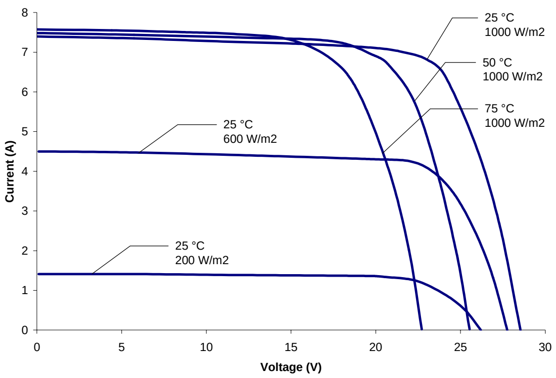

Figure 1 – PV module I-V curves.

ENVIRONMENTAL EFFECTS ON PV MODULES

PV modules are most often characterized by their power rating at Standard Test Conditions (STC), that is, under a normal irradiance of 1000 W/m^2, with a cell temperature equal to 25 °C, and with a spectral distribution corresponding to air mass 1.5. In practice, the power delivered by the module is lower because of effects due to irradiance level, operating temperature, angle of incidence, spectral distribution of irradiance, and so on. Quantifying the relative importance of these various effects is a key interest of a simulation program, and is the object of this section.

Solar radiation

Solar radiation is the main influence on PV module output. Roughly speaking, module output is proportional to the irradiance level. (This is not true, however, in the presence of partial shading, as will be seen later). This 'proportionality' should not be interpreted in a true proportionality law. In practical terms only the short-circuit current is almost exactly proportional to irradiance. For the maximum power the relationship is more an affine one (i.e. linear with offset), as shown in Figure 2 which is derived from data measured by Kenny *et al.* (2003). Representing correctly the offset (i.e. predicting module performance at low light levels) is a major challenge.

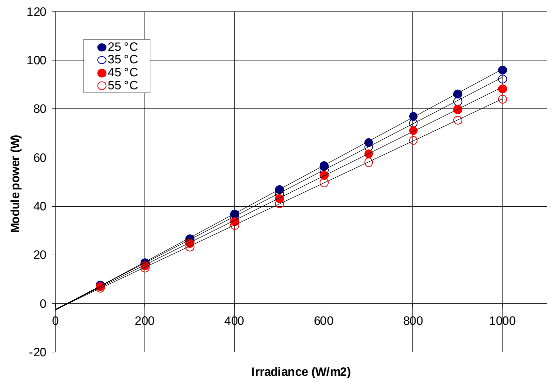

Figure 2 - Power as a function of irradiance. Data from Kenny et al., 2003.

Temperature

Temperature is the second most important effect. Typically voltage decreases with increasing temperature, and current increases (although slightly), the combined effect being that power decreases. Temperature coefficients for the maximum power are reported as -0.5 %/°C for poly-Si and -0.25 %/°C for a-Si (King *et al.*, 1992; see also King *et al.*, 2000); values of -0.4 %/°C are also reported (Sick and Erge, 1996) for c-Si, as well as values of -0.45 %/°C for c-Si and -0.22 %/°C for a-Si (Ransome and Wohlgemuth, 2002). A poly-crystalline module operating typically at 45 °C will therefore produce roughly 10% less power than predicted by its nominal STC rating.

The effect on annual energy production was found in King *et al.* (1992) to be between -1% and -6% for mc-Si and between 0% and -2% for a-Si. However this depends on many factors such as mounting structure and local wind conditions. The values may be higher for poorly ventilated building-integrated PV modules. Values up to 11% are reported in Xantrex (2001).

Angle of incidence

Optical losses vary with the angle of incidence of light striking the module. In particularly there are increased reflection losses at the module's air/glass interface when angles of incidence are above 60°. At very high angles of incidence the losses are very significant (approaching 100% at 90° incidence). However modules are often properly oriented (for example facing the equator with a tilt equal to the latitude) and for most hours receive light under an appropriate incidence angle, so over a whole year the decrease in energy production imputable to angle of incidence effects is estimated in the range 1% to 5%; and on a monthly basis, in the range 0% to 9% (King *et al.*, 1992).

Spectral distribution

The response of solar cells varies depending on the spectral composition of incident light. For example amorphous Si cells respond better in the 'blue' part of the spectrum than in the 'red', and therefore will proportionally deliver more power in the middle of the day, when the sun is high in the sky and 'bluer', than in the early morning or late afternoon, when it is low on the horizon and therefore 'redder'. Similarly some modules will exhibit enhanced or reduced performance depending on the presence of clouds.

For individual hours these effects can range from +5 to -50% depending on module technology (King *et al.*, 1992). However, as was the case for angle of incidence, these effects tend to be much lower when the sun is high in the sky, which is also when the module produces more energy; so over longer periods of time the effect is much smaller, and is reported in the range +1% to -4% on a monthly basis, and 0% to -3% on a yearly basis. Similar values can also be found in Nann and Emery (1992).

Spectral effects may be somewhat higher for amorphous silicon modules, as reported in Kenny *et al.* (2002); they are reported to be in the range ±7% on a monthly basis in Gottschalg *et al.* (2002).

Uncertainty in the output of crystalline PV modules

PV modules are normally rated by the manufacturer at a given wattage. However, there is no standard way of reporting module power in manufacturers' literature. Several possible effects should be taken into consideration:

- Brand new modules placed in the field usually see their maximum power decrease by a few percents within a few hours of exposure (see Cereghetti *et al.*, 2001; some specifications sheets from manufacturers also mention this, but for commercial reasons give a period of months rather than hours).
- Modules are normally sorted in 'bins' according to their rated power – for example the best modules will be 100 W and the second-best will be 95 W (on binning see also Ransome and Wohlgemuth, 2002). A same batch can therefore contain modules rated within a certain fork, sometimes specified by the manufacturer in the form of a power tolerance (for example ± 5%, or +0/-5%).
- Cereghetti *et al.* (2001) show that power measurement of new modules was lower than nominal values stated by manufacturers in 12 out of 13 modules tested, with values lower by as much as 23%. The power rating declared by the manufacturer is sometimes 'fictitious'.

Uncertainty in the output of amorphous PV modules

Amorphous modules suffer the same uncertainties as their crystalline counterparts, however there is an added uncertainty that is inherent to the technology, namely that the module suffers from a light-induced degradation; this degradation results in an initial loss of efficiency reaching typically 20% within the first six months (King *et al.*, 2000). Complicating the picture is that some of this initial loss may be reversible, for example the efficiency increases during hot periods due to self-annealing (which may induce variations of typically ±4% around the stabilized power, as shown in King *et al.*, 2000).

Normally, manufacturers provide a 'stabilized' power rating for their modules, which takes into account the light-induced degradation. For that reason and because not all modules degrade at the same rate, it may happen that modules in the field will perform better than what they are rated at, as shown in Ransome and Wohlgemuth (2002). However the uncertainty as to what the module will deliver once installed is larger than for crystalline modules.

Ageing

The power rating of PV modules tends to degrade slowly over time. Depending on module technology, encapsulant technology, and so on, the ageing is more or less pronounced – for some newer technologies it may not be fully known. For crystalline silicon the power loss has been reported between 0.2% and 0.7% per year, with a typical value of 5.5% over the lifetime of the module (Dunlop, 2003). This is in addition to the initial light degradation mentioned earlier. Module manufacturers usually guarantee the power of their modules over their lifetime; for example, that the module power will not fall below 90% of its original value after 12 years and not below 80% after 25 years.

Mismatch

Because of slight variations in the electrical characteristics of the modules within an array, the maximum power output of the total PV array is always less than the sum of the maximum outputs of the individual modules. The associated losses are called mismatch losses. They are usually minimized by connecting modules with very similar characteristics, however mismatch losses of a few percent should be taken into account (CEC, 2001 recommends at least 2%) .

Soil and dirt

Soil and dirt accumulate on the front surface of the PV module and therefore limit the amount of solar radiation that reaches the solar cell. The amount of dirt will depend on factors such as presence of dust and pollution, amount and frequency of rain, and array orientation. The magnitude of this effect is hard to estimate; values range from 0 to 15% with a recommended value of 7% (CEC, 2001). Values up to 10% are reported in Sick and Erge (1996).

Snow

The accumulation of snow on the PV module may be a problem in some regions, particularly in Canada where some areas of the country are susceptible to heavy snow fall. Through natural heating, PV modules can often shed accumulated snow by themselves after a few days. However this is true only if (1) the accumulation of snow is not too important, so the PV module still receives enough sunlight to warm up, and (2) the slope of the PV array is steep enough, for example greater than 45 or 60°. If these conditions are not met the PV array may not produce any significant amount of power during those months with large amounts of snow.

Partial shading

Shading part of a PV module has a very dramatic effect on its power output. Shading even a small fraction (for example, 5%) of the module may result in a very large reduction (50% or more) of the module power. This is due to the fact that, in a string of cells connected in series, the cell with the lowest illumination determines the operating current of the whole string (this is compared in Sick and Erge (1996) to pressing a water hose tight at one point, preventing the flow of water in the whole hose). Furthermore, shaded cells may become reverse-biased and dissipate energy forced into them by other cells in the string, creating 'hot spots' which have the potential of thermally destroying the module. For those two reasons, the occurrence of shadows on PV modules should be avoided at all costs. This includes shading by utility poles, chimneys, trees, by other buildings or and by other parts of the same building.

Diodes and wiring

Losses due to blocking diodes and wiring are estimated around 3% (Xantrex, 2001; CEC, 2001), even for a very well-designed system.

Summary

The following table provides a summary of secondary effects in PV arrays, with an estimate of their effect on monthly energy production estimates. Similar tables can be found in Xantrex (2001) and King *et al.* (1992).

Table 1 – Summary of secondary effects in PV arrays.

EFFECT	RANGE
Temperature	1% to 10%
Angle of incidence	1% to 5%
Spectral distribution	0% to -3%
Uncertainty in manufacturer's rating	0 to 5% or more
Ageing	5% over lifetime
Mismatch	2%
Soil and dirt	0 to 15%
Snow	Location dependent
Partial shading	Location dependent
Diodes and wiring	3%

THE ESP-R PV MODELS

Description

The ESP-r PV model is described in Kelly (1998) and in Clarke *et al.* (1997). The model actually comprises two models: a simple one based on a constant efficiency, and a more elaborate one based on an equivalent one-diode model.

Photovoltaics in ESP-r are modeled as an active material, which can be located at any node inside a construction. An example is shown in Figure 3; this example is taken from the choices of silicon PV modules proposed in ESP-r and corresponds to a BP Solar BP 585 module. The construction is simplified into a pane of 3 mm toughened low-iron glass, and a layer of ethylene vinyl acetate (EVA) and tedlar, which also represents the cells. For the purpose of the simulation, the active material (the silicon solar cell) is located at the middle node of the EVA/tedlar layer. The temperature of that node is assumed to be representative of that of the PV module, and solar radiation reaching the cell is set equal to solar radiation incident on the glazing system. Knowing temperature and solar radiation it is possible to calculate the power output of the PV cell. Since it is evacuated in the form of electric power, this power output is then subtracted from the nodal absorption of the incident radiation. The energy balance and heat flow calculation is handled by ESP-r, in the same way it would normally calculate heat transfer through a construction. This simulates quite effectively the absorption of solar radiation at the cell level and its diffusion as heat through the module assembly and, possibly, the envelope of the building.

If the module is modeled as an opaque construction, the part of incident radiation that is converted to electricity is deducted from the short-wave radiation absorbed at the front of the module. If the module is modeled as a transparent assembly, half of the converted radiation is deducted from short-wave radiation absorbed at the front and half from the short-wave radiation absorbed at the back.

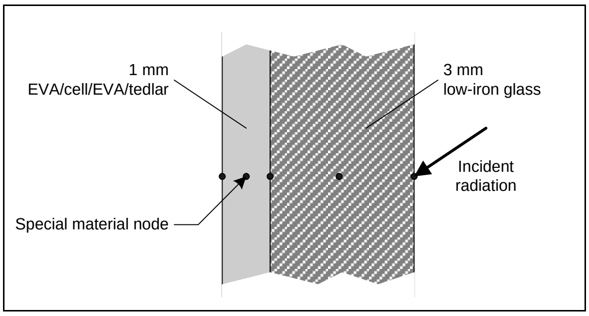

Figure 3 – ESP-r model of a PV module.

When the simple PV model is used, the power output of the module is calculated based on a constant efficiency. In the more complicated crystalline silicon model, based on a model by Buresch (1983), the electrical behaviour of the module is modelled through the use of an equivalent circuit, shown in Figure 4. The equations describing the circuit include an explicit irradiance dependency; the diode is modelled as a thermally activated device (through an Arrhenius relation in the form exp(eV/kT) term, with T the absolute temperature of the module, k the Boltzman constant, e the charge of the electron and V the voltage) to account for variations of module performance with temperature.

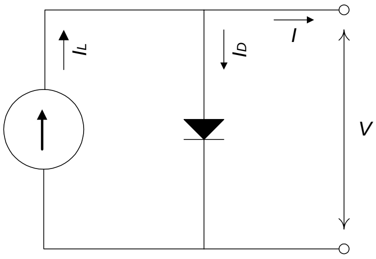

Figure 4 – Equivalent one-diode circuit in ESP-r.

Discussion

The ESP-r photovoltaic model was developed for ease of use and has proved fit for that purpose on a number of occasions. The basic premises of the ESP-r PV model are valid: the module can be modeled as a special material which takes away some of the heat transferred through it. However some of its aspects are somewhat too simplistic:

- Module power is calculated using solar radiation incident on the *outside* surface of the module assembly, rather than radiation at the active material node itself. It is true that electrical characteristics of the PV module entered by the user take into account light reflection on the front surface; but these characteristics are measured only under normal incidence. In practice solar radiation reaching the cell depends strongly on the angle of incidence of sunlight on the module. Since ESP-r handles this kind of calculation quite well, solar radiation reaching the active material node itself should be used, rather than solar radiation on the outside surface. This would also help represent custom-made or architectural PV modules, for which the characteristics of the *cell* can be known but the assembly itself has not been tested.
- The Buresch model upon which the ESP-r model is based is too simplistic, particularly because it does not include a series resistance. The shape of the I-V curve in the absence of a series resistance may differ significantly from the real I-V curve, particularly in the right part of the curve (near the maximum power and open-circuit conditions). Figure 5 illustrates the influence of the series resistance on the shape of the I-V curve. A complete equivalent circuit, including series resistance, will be seen in Figure 6.

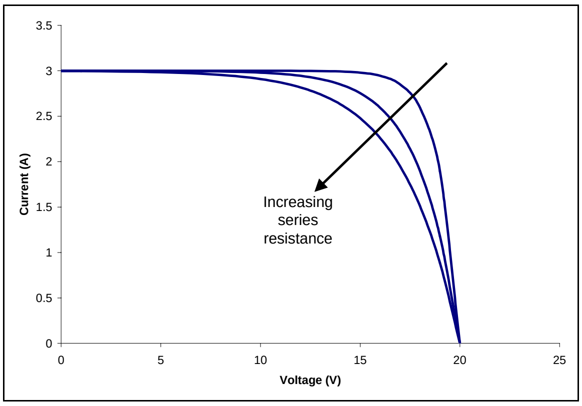

Figure 5 – Effect of series resistance on the I-V characteristics of a solar cell.

- The ESP-r model assumes a pre-determined temperature dependence of some of its parameters, particularly the diode current and the light generated current. However experience shows that such functional forms are somewhat simplistic and do not represent properly the module’s behaviour (in part because there are many temperature-dependent effects in a module, not all of which follow simple physical laws; and in part because the equivalent circuit used is too simplistic and does not include the series resistance).

To alleviate these limitations, it is suggested to improve the ESP-r PV model, as will be explained now.

PROPOSED PV MODEL

To improve on the PV model currently in ESP-r, a combination of three models is proposed:

- a simple model based on constant efficiency;
- an equivalent one-diode model;
- a more complicated model based on the Sandia model.

All three models would share the same method for temperature calculation, which is reviewed first; the models are then described in detail.

Temperature calculation

Most PV models described in the literature include a calculation of cell temperature, sometimes utilizing the concept of nominal operating cell temperature (NOCT). However it is probably best to leave temperature calculation to ESP-r itself, as is done now, since ESP-r is able to take into account not only the thermal characteristics of the module assembly itself, but also those of the module surroundings. For example a module will operate at a different temperature depending on whether it is mounted on a rack or integrated in a façade.

A problem arises from the temperature calculation, namely that the amount of heat released by the module to its surroundings depends on its efficiency, which itself depends on the module temperature, which cannot be known without calculating a heat balance with the surroundings. To avoid solving simultaneously for module temperature and efficiency, one can safely assume that temperature calculations can be uncoupled from power calculations, and calculate the module's temperature assuming that it operates a the maximum power point, as explained by Thevenard *et al.* (1992). An alternative is to use for the current time step the module temperature calculated at the previous time step. However this last approach should be discouraged, especially with hourly time steps, as PV modules have very little thermal inertia and, under changing conditions, the module temperature at the previous hour will likely be inconsistent with the radiation level for the current hour.

Simple model

The simple model based on a constant efficiency currently used in ESP-r is adequate. It would benefit, however, from using solar radiation actually reaching the active material, rather than incident on the outside surface, in order to properly take into account angle of incidence effects.

Equivalent one-diode model

A more complete model would be based on an equivalent one-diode circuit. This circuit should include the representation of the series resistance, which cannot be ignored without a significant loss of accuracy. Such a circuit is shown in Figure 6.

Several such models exist in the literature; two good examples, which derive the I-V curves in somewhat different ways, are the TRNSYS model (Duffie and Beckman, 1991) and the WATSUN-PV model (Thevenard *et al.*, 1992). These models characterize the equivalent circuit using only parameters that are widely available to the users, such as the open-circuit voltage, short circuit current, and maximum power point voltage and current. They also explicitly take into account variation of these parameters with temperature. Temperature coefficients are routinely published in module specifications by manufacturers and can be used for that purpose. This explicit and empirical temperature dependency of the I-V curve varies according to module technology and better represents the behaviour of individual modules than the assumed functional form used by the present ESP-r model.

Which of the two models should be implemented is mostly a matter of taste. The author has a slight preference for the WATSUN-PV model, which is based on simpler equations than the TRNSYS model. This latter model requires parameters such as the energy bandgap of the material or the number of cells in series, whereas the WATSUN-PV model limits itself to readily available quantities (short circuit current, open circuit voltage, maximum power point, and their variations with temperature). Both models have been found to model the behavior of PV modules to a reasonable degree of accuracy.

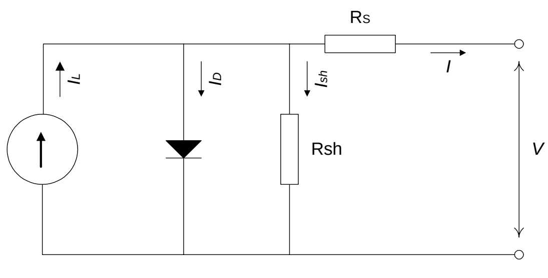

Figure 6 – Proposed equivalent one-diode circuit.

Sandia model

Finally the model developed by Sandia National Laboratories (King *et al.*, 1998; King *et al.*, 2004) could also be implemented. The Sandia model is a totally empirical model describing how the module's I-V curve varies with parameters such as irradiance level, module temperature, angle of incidence, and spectral distribution (through a term dependent on air mass). The strength of this model is that it is fairly complete. It tries to take into account most of the phenomena that influence the power output of a PV module. According to its authors, it also compares favorably with field tests.

The model's main drawback is that it requires the experimental determination of a very large number of parameters (30 or so). No manufacturer provides that much information about their module. Sandia does make available a database of parameters for over 120 modules, however each new module coming to market needs to be tested according to their method to obtain the parameters required by the model. To be of any use, the incorporation of Sandia's model into ESP-r would also require the inclusion of the Sandia database.

Other common features of the models

All three models should be complemented by algorithms to take explicitly into account the various effects listed in the previous version of the paper: mismatch losses, losses due to soil, dirt or snow; and diodes and wiring. The algorithms could be as simple as derating short-circuit and maximum power point currents according to losses specified by the user. The models should also include (as is done now) a provision to reduce the output of modules in case of shading; such an algorithm would also benefit from an improvement of the shading algorithm in ESP-r.

BALANCE OF SYSTEM

Photovoltaic modules constitute an essential part of residential PV systems, but the balance of system requires also attention. Inverter efficiency, for example, should not be assumed constant, but be represented by an efficiency curve such as the one shown in Figure 7.

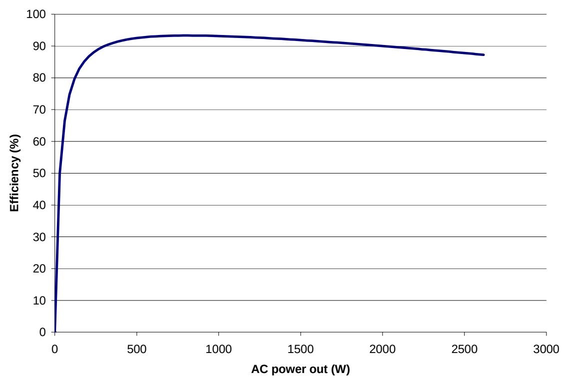

Figure 7 – Typical inverter efficiency curve.

CONCLUSIONS

The current ESP-r PV model is adequate to predict the impact of photovoltaics on the building's thermal energy balance, but may lack in accuracy to predict the energy production of the PV system. To achieve both goals at once it is suggested to improve or rewrite the PV models in ESP-r.

All phenomena affecting the power output of PV modules should be explicitly taken into account: solar radiation intensity, cell temperature, angle of incidence, spectral distribution, uncertainty in manufacturer's ratings, ageing, mismatch, soil and dirt, snow, partial shading, diodes and wiring. This would provide a more realistic estimate of the probable output of the PV system over its lifetime.

Three models should be implemented:

- A simple model based on constant efficiency (as is done now).
- A more complicated model based on a one-diode equivalent circuit such as the TRNSYS or WATSUN-PV models. The one-diode model should include the representation of the series resistance, which cannot be ignored without a significant loss of accuracy. The model should use parameters that are widely available to the user, and expend on the crystalline silicon model currently in ESP-r by providing explicit temperature of short circuit current, open-circuit voltage and maximum power point.
- The Sandia model could also be considered for inclusion. This would also require using Sandia's database of PV modules since most of the parameters required by the model are not available from manufacturer's data sheets.

The models should calculate the power output based on the absorbed solar radiation in the PV material layer, rather than at the outside surface. Module temperature calculations should be handled by ESP-r, as is done now. To simplify the calculation, module temperature can be safely uncoupled from power calculations; it is not recommended to use temperature from the previous time step (i.e. cell temperature for the current hour has to be consistent with the radiation level for the current hour, not for the previous hour).

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