Evaluation of Proposed Photovoltaic Energy Rating Standard: Validation against outdoor measurements

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Abstract

Effective energy production is the ultimate purpose of photovoltaic devices and thus should be considered in describing device performance. This paper investigates the impact and relevance of the proposed IEC energy rating standard reference days on the energy prediction of various device technologies in the UK climate and found MIMT and MIHT are most relevant. Three different module technologies have been tested over a wide range of module temperature (T_{mod}) and irradiance (G) level in outdoor measurement conditions. Performance of each technology is calculated in terms of distribution of energy generation with the main influencing parameters. The paper also compares the power distributions (with irradiance and temperature) of crystalline silicon modules in indoor and outdoor measurement conditions. Sensitivity analysis of energy yield estimation and its modelling accuracy are analysed for three devices with the different combinations of G_{mod} and T_{mod} and its found that c-Si and a-Si device technologies underestimated by 7.6% and 6.8% but CIGS module overestimated by 0.05% in the UK climate.

Introduction

To date, the main performance indicator for photovoltaic (PV) modules is the Standard Test Conditions (STC) measurement which is a laboratory based test at specified irradiance, module temperature, angle of incidence and spectrum [5-6]. However, the module energy yield under different environmental conditions (as experienced in real operation) can not described by the STC. Considering the increasing demand for PV technologies, energy rating is becoming a distinguishing factor between the different technologies and will be of increasing importance in the design of PV systems. At present, PV installers only have watt peak (W_p) information for designing and sizing the systems, which is not sufficient. Varying environmental conditions will cause variations in performance which will be different for different device technologies and operating climates.

To set up a benchmark, the IEC (International Electrotechnical Commission) is working to develop a new energy rating standard, considering a wide range of climatic operating conditions through the specification of environmental data for a number of reference days (IEC 61853) [2-4]. A draft is in preparation which should address this market need and give a useful energy predictor to compare different device technologies over the entire range of operating environments seen by PV systems.

This paper investigates the applicability of this draft for the UK climate and aims at investigating the achievable accuracies with the current draft. This draft is by no means final and might very well change when it is put forwards for international voting. However, it is interesting to evaluate applicability of this standard to various climates and thus contribute to the international validation efforts.

Standard Reference Days

The original IEC draft standard represented six reference days [1] to cover extreme combinations of ambient temperature and irradiance to estimate the energy yield of the module. These reference days are tabulated with irradiance, ambient temperature, wind speed, angle of incidence and spectral distribution over each day, with the cases labelled as:

HIHT (High irradiance, high temperature)
HILT (High irradiance, low temperature)
MIMT (Medium irradiance, medium temperature)

MIHT (Medium irradiance, high temperature)
LILT (Low irradiance, low temperature)
NICE (Normal Irradiance, cool environment)

This paper discusses the influence of irradiance and temperature only, with spectral and incident angle effects to be investigated in follow-on work. The above reference days are distinguished in figure 1 for a typical crystalline silicon device with different module temperatures (T_{mod}) and incident irradiance on the module (G_{mod}). T_{mod} is calculated considering the effects of irradiance and wind speed with the given ambient temperature. G_{mod} is calculated considering the given beam and diffuse irradiance components of the different reference days and the transmittance values with the different angle of incidence (AOI), measured for the module. Reference day conditions are tabulated at hourly intervals and in the figure, each point is one of these entries.

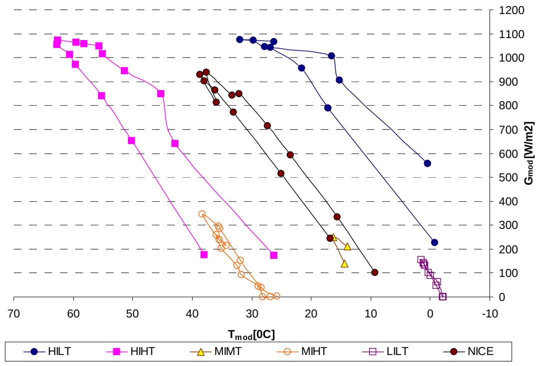

Figure 1: Characteristics of the six standard reference days with different irradiance and temperature levels

Measurement Method

The aim of this paper is to validate this standard for the UK, which requires the input of realistic environmental and module data.

Three different module technologies are considered in this paper and their datasheet STC ratings are given in table 1.

Device	Area [m2]	Isc [A]	Voc [v]	Pmax [W]
c-Si	0.296875	2.48	21.5	40
a-Si	0.0351002	0.165	22.8	2.1
CIGS	0.05184	0.390	22.9	5

Table1: Module parameters at STC

In-plane irradiance, module temperatures and I-V curves are measured every ten minutes in the outdoor test facilities at CREST in the period April 2007 to January 2008.

The measured data of irradiance and module temperatures was sorted by binning and in this manner, an irradiance-temperature matrix has been generated to investigate the frequency of measurements taken, average power distribution and energy yield with their STC-normalized values.

Indoor measurement of I-V curves are made according to the proposed IEC draft standard [2] based on irradiance and temperature settings in a pulsed solar simulator at Arsenal research and are then analysed at CREST.

Results and Discussions

The matrices of count of bins for all devices are normalized to their total number of measurements taken to get the frequency distribution of the measurements and its found that all modules also shows similar behaviours within the same range of T_{mod} and G_{mod}. Bins used for frequency distribution of the measurements are sorted by 50W/m^2 G_{mod} and 2^0C T_{mod}.

The measurement matrix of average power generation of the modules has been generated with respect to module temperature and irradiance and then the matrices were normalized to their respective STC values. Figure 2 shows the power generation of a c-Si module in outdoor measurement conditions at CREST and compared with the Arsenal indoor measurements matrix of power (Figure 3) under similar performance conditions of T_{mod} and G_{mod} but it should be noted that the modules used for indoor and outdoor measurements are different modules of same technology and most likely of the same batch.

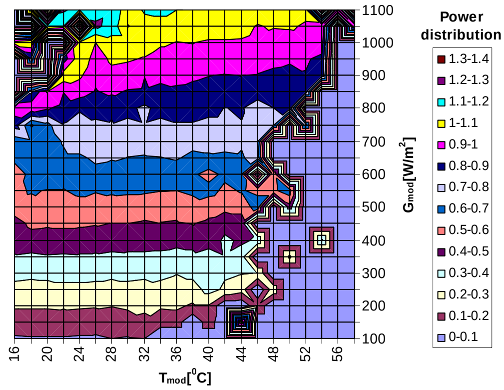

Figure 2: Contour plot of power with respect to T_{mod} and G_{mod} extracted from outdoor measurements for a c-Si device

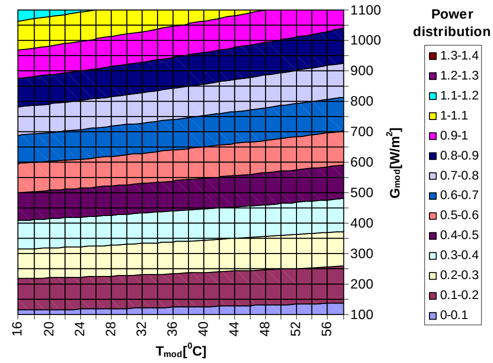

Figure 3: Contour plot of power with respect to T_{mod} and G_{mod} extracted from indoor measurements for a c-Si device

Inhomogeneous power distributions occurred in outdoor conditions compared to indoor measurement conditions, but broadly the same range of power distributions occurred at lower levels of G_{mod}. There is a very limited amount of power generated above 50^0C of T_{mod} in outdoor conditions at Loughborough.

The following figure 4 shows how the energy yield of a c-Si device is distributed with respect to the same performance parameters. The sum of energy in each bin has been normalised by the total to show the fraction of energy generated. Other device shows similar results.

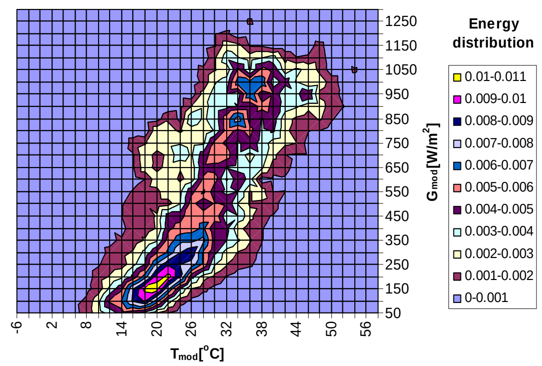

Figure 4: Energy yield distribution of a c-Si module in the Loughborough climate

The energy distribution in Figure 4 is noteworthy in that the maximum energy is generated in the range of 150 W/m^2 and around 20 degrees. This is very different to what has been reported for other locations, where high temperature and irradiance data dominates energy production. This then also allows a statement on the applicability of standard days as originally proposed.

Comparing these results with the six reference days of the draft IEC standard, it has been found that HIHT, HILT, NICE and LILT are not relevant in the context of the UK's climatic conditions, since very little of the total energy production is under such conditions. As stated above, the majority of energy generation has taken place in fact in the range 15^0C to 23^0C module temperature and 50 W/m^2 to 250W/m^2 incident irradiance for all module technologies tested in this study. The most relevant reference days are thus the medium irradiance-medium temperature (MIMT) and medium irradiance-high temperature (MIHT).

Based on outdoor measurement at CREST, the corresponding maximum power (P_{max}) of different modules are calculated with respect to G_{mod} and $T_{mod.}$ P_{max} is estimated by the following equation.

$$P_{max} = (C_1{*}G_{mod}+C_2)T_{mod} + C_3{*}G_{mod} + C_4$$

Coefficients are calculated using linear fitting against G_{mod} and $T_{mod.}$ Different coefficients for different modules are given in table 2.

Device	c-Si	a-Si	CIGS
C_1	-5.27E-06	5.591E-06	-4.8E-06
C_2	0.002259	0.001519	0.001497
C_3	0.001077	0.000817	0.001124
C_4	-0.04493	-0.02634	0.004642

Energy yield is calculated from the IEC method and its modelling accuracy is calculated for three technologies. The results demonstrate that the c-Si and a-Si module outputs are underestimated by 7.6% and 6.8% but CIGS module overestimated by 0.05%. These values are for G-T calculations only, i.e. the differences between measured and modelled energy yield might be better if the spectral correction are applied. One should also not put too much weight on the CIGS result, as this might be only due to fortunate circumstances.

A sensitivity analysis has been performed, by fixing different combinations of G_{mod} and T_{mod} in the model. Figure 5 and 6 describe the percentage error of modelled and measured energy production against different fixed T_{mod} with varying G_{mod} and different fixed G_{mod} with varying T_{mod}.

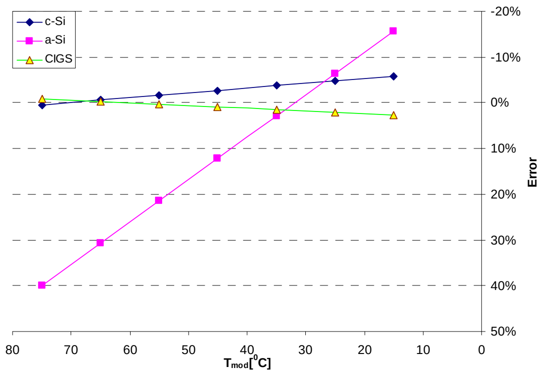

Figure 5: Model accuracy of energy yield estimation - sensitivity to module temperature

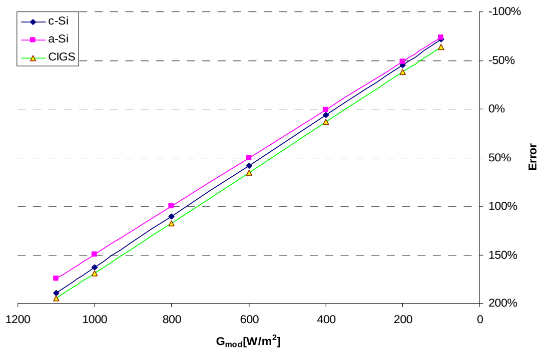

Figure 6: Model accuracy of energy yield estimation - sensitivity to incident irradiance

The rates of increase in errors with fixed temperatures are 0.10/^{0}C, 0.92/^{0}C and 0.05/^{0}C respectively for c-Si, a-SI and CIGS modules. This would indicate that the extraction of the thermal coefficient for a-Si is not ideal, as it is normally considered to be very tolerant of elevated operating temperatures. It is also surprising the error increases with decreasing temperatures and is actually quite significant close to the dominant area of energy generations. The rates of increase in errors with altered fixed irradiances are 0.26/Wm^{-2}, 0.24/Wm^{-2} and 0.25/Wm^{-2} respectively for c-Si, a-SI and CIGS modules. Errors between modelled and measured energy yield increases with the increasing G_{mod} for all three module technologies in the UK climate, this is because of the major energy generation takes place at medium irradiance level.

Conclusions

Energy yield distributions from outdoor measurements in the UK have been extracted and compared with the six reference days of the draft IEC standard 61853.

Three different PV technologies have been studied and, considering the major energy generation in UK, it has been found that MIMT and MIHT are the most relevant reference days in this environment.

Modelling accuracy rate have been found 0.10/^{0}C for c-Si and 0.05/^{0}C for CIGS technology with altered fixed T_{mod} with variable irradiances compared to a-Si which is relatively higher then others but with the altered fixed G_{mod} all devices shows similar result in the range 0.24/Wm^{-2} – 0.26/Wm^{-2}.

Determination of the relevant reference days for different locations with varying climatic conditions needs to be carried out for full evaluation of this energy rating standard as well as inclusion of the other factors influencing device performance. This is the subject of ongoing work at CREST.

Acknowledgements

This work is supported by the Engineering and Physical Sciences Research Council under grant number EP/D078431/1. The authors are grateful to Stefan Mau, formally of Arsenal Research in Vienna, who measured and supplied the data shown in Figure 3.

References

[1] IEC 61853-draft standard. Performance Testing and Energy Rating of Terrestrial Photovoltaic (PV) Modules., January 2001
[2] IEC 61853-1 Draft H Standard, “Photovoltaic (PV) Module Performance Testing and Energy Rating-Part 1: Irradiance and Temperature Performance Measurements and Power Rating, October 2007
[3] IEC 61853-2 Draft E Standard, “Photovoltaic (PV) Module Performance Testing and Energy Rating-Part 2: Spectral Response, Incidence Angle and Module Operating Temperature Measurements, 2007
[4] IEC 61853-3 Draft C Standard, “Photovoltaic (PV) Module Performance Testing and Energy Rating-Part 3: Energy Rating of PV Modules, 2007
[5] Mau,S.. et al. Quantifying Environmental Effects for Different Devices Technologies Based on Proposed Energy Rating Standard, Proceedings of the 22nd European Photovoltaic Solar Energy Conference, Fiera Milano, September 2007.
[5] IEC 60904-1, Measurement of photovoltaic current-voltage characteristics.
[6] IEC 60904-3, Measurement principles for terrestrial photovoltaic solar devices with reference spectral irradiance data.