EVALUATING THE STATE OF THE ART OF PHOTOVOLTAIC PERFORMANCE MODELLING IN EUROPE

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ABSTRACT: There are many models currently available which provide detailed information regarding the performance of PV modules. This paper reviews, as part of the European co-ordination action PV-Catapult, the different performance modelling approaches currently developed by European research institutions. The aim of this paper is to provide an overview of modelling approaches available and define the inputs required for each model. This will be used to investigate the accuracy of these models for different European climatic conditions in a second stage of the project.

All methods are reviewed, highlighting strengths and weaknesses of each. None of the methods consider temporal variations, such as degradation in the case of amorphous silicon. This paper investigates the impact this has on the year-to-year performance translation of such devices. Furthermore there is very little consideration of the incident spectrum, which affects wide band gap devices and multi-bandgap devices disproportionately, but this effect commonly is folded into irradiance and temperature effects. The implications of these are discussed based on current sales practice of quoting straight kWh/kWp, indicating the need for a better, technology independent comparator based on realistic energy production, rather than today's STC laboratory efficiency. The results indicate that most models can predict energy yield within 10%.

Keywords: Energy Rating, Modelling, Performance

1 INTRODUCTION

The difficulty of accurately predicting long-term PV module performance in different European climates has increased with new production technologies. Several models have been developed by different groups across Europe. This paper is part of the co-ordination action 'PV-Catapult' funded by the European Commission. It will review the different available models and assess their suitability and relevance to PV system performance around Europe. The aim is to investigate strengths and weaknesses in order to give guidance for future improvement in yield prediction. This paper investigates the error margins of the different modelling approaches in use across the EU.

Different methods for modelling the energy production of photovoltaic systems have been presented, ranging from those using measure-correlate-predict (e.g. Ransome and Wohlgemuth [1]) to those based on physical device models [2]. In between there are models which parameterize laboratory measurements, matrix methods and realistic reporting conditions (RRC) approaches [3-6]). The suitability of each model for different device technologies (crystalline silicon and thin film devices, single and multi-junction) is investigated. Measure-correlate-predict methods cannot be investigated as the data basis available to the project at this time does not contain sufficient identical modules at different sites. Thus, this paper limits its investigation to temporal variations, i.e. year to year predictions, at different locations.

1.1 Review of Modelling Methods

The different models calculate the real efficiency, performance ratio (PR) and energy yield of modules. These figures of merit can easily be translated into each other. A large range of input requirements and specifications were identified which depend on the measurement system in place by the different centers. The models used in this work are listed in Table **I**, together with the groups operating them.

Name of Modelling Method	Developed By
Matrix	LEEE
MOTHERPV	CEA
Back Temperature	CEA
On-Line Yearly Yield Simulator	ECN
SSC	CREST

Table **I**: List of the performance models reviewed in this work and the research centers developing them.

Matrix Method: This approach uses a power matrix or performance surface as a function of irradiance and ambient temperature. The energy yield is then calculated by multiplication of this matrix with a climatic condition occurrence matrix. The climatic matrix is location specific. This is a modified and simplified version of the equations published by Sandia National Laboratories [9].The method requires the end-user to only know the monthly horizontal irradiance and average ambient temperature of his site (both readily available). The method has been validated for open-rack-mounted c-Si with an indicated error for annual energy yield of ±1.1%

if the real monthly meteo data $G_{hor,glob}$ and T_{amb} are available. The power matrix is derived either from indoor measurements or through a measure-correlate-predict method from outdoor measurements as in equations 1 and 2.

$$I_m = I_{m,stc} \cdot G/1000 \cdot [1+\alpha \cdot (\Delta T \cdot G/1000 + T_a - 25)] \quad (1)$$

$$Vm = Vm,stc + C0 \cdot \ln(G/1000) + C1 \cdot (\ln(G/1000))^2 + \beta \cdot (\Delta T \cdot G/1000 + Ta - 25) \quad (2)$$

where:

$I_{m,stc}$	maximum power point current @ STC
α	temperature coefficient of I_m @ 1000W/m²
ΔT	temperature difference T_{cell}-T_a @ 1000W/m²
$V_{m,stc}$	maximum power point voltage @ STC
C_0 C_1	module specific parameter
β	temperature coefficient of V_m @ 1000W/m²

Meteorological, Optical and Thermal Histories for Energy Rating in Photovoltaics (MOTHERPV): This is still an experimental method in development by CEA. It allows the prediction of the performance ratio (PR) for sites with a good knowledge of the frequency distribution function of the incoming energy and the module back temperature as functions of irradiance. This prediction requires a short campaign of measurements in a given site with enough irradiance and temperature levels.

For each level of irradiance, the module efficiency is translated from the efficiency measured during the reference period, according to the formula in equation 3:

$$\eta(G) = \eta(G_{ref})\left(1+\alpha(G)\left(T_{bom}(G) - T_{bom\ ref}(G)\right)\right) \quad (3)$$

Where $\alpha(G)$ is the temperature coefficient of the module efficiency at the specified irradiance, when expressed as a function of the module back temperature.

$T_{bom}(G)$ is the measured average temperature for the new period and $T_{bom\ ref}(G)$ is the measured average temperature for the reference period.

Module Back Temperature Method: This method uses the fact that the average (PR) is a linear function of the average module back temperature during different periods of time. This back of module temperature may be calculated from ambient temperature, in-plane irradiance and wind speed. Its accuracy for the same site has been determined as within 1%, based on a one-year dataset. Model performance assessment for other sites is ongoing - it is anticipated to provide the predicted energy output for sites with a similar climate to a good approximation [10].

On-Line Yearly Yield Simulator: This method uses empirical laboratory translation for indoor to outdoor measured $\eta_{mpp}(G,T)$. The efficiency is related to ambient temperature and the in-plane irradiance. The in-plane irradiance and module temperatures are calculated using the following steps:

In plane irradiance: from hourly global irradiance values on the horizontal plane (TRY).

Step 1: The calculation of the direct and diffuse components of irradiance via Orgill and Hollands correlation [11]. The correlation equation for hourly diffuse irradiance on a horizontal plane is utilized.

Step 2: The calculation of the in-plane irradiance using the Perez model [12].

Step 3: The calculation of the reflection losses for non-normal incidence angle. This calculation is based on the assumption that the irradiance on the horizontal plane (hourly input data) is measured with a pyranometer and that the PV-module has a glass cover.

Step 4: The calculation of the device temperature using ambient temperature and in-plane irradiance as in equation 3.

$$T_{module} = T_{ambient} + G_{in\ plane} * k \quad (3)$$

where T_{module} is the device temperature; $T_{ambient}$ is ambient temperature obtained from hourly values (TRY); $G_{in\ plane}$ is the in-plane irradiance; and k is the empirical value $K/(W/m^2)$.

(For free standing modules k=0.015, for roof integrated modules k=0.04.

The method, which is publicly available at http://www.ecn.nl/solar/yield/index2.html, is straightforward and includes DC/AC-inverter losses.

SSC (Site Specific Conditions): The SSC approach builds on the RRC method [3] and uses a measure-correlate-predict approach to model and predict the energy yield for PV modules. Using numerical methods SSC systematically separates and quantifies the effects of non-STC operating conditions. Its mathematical method is given in equation 4. Based solely on outdoor measurements this model can predict energy yield within 10% for most modules at the same or different sites. As most sites do not have spectral data, the model is restricted to irradiance and temperature effects here. It is, however, anticipated that the model will overestimate the output, due to the lack of spectral losses and reflection losses.

$$\eta_{SSC} = r_T \cdot r_G \cdot r_X \times \eta_{STC} \quad (4)$$

where the terms are defined as follows: n_{SSC} is the SSC efficiency; n_{STC} is the STC efficiency; r_Y is the factor which describes the effect of each variable as they deviate form STC: T is temperature; G is irradiance is for others, like spectrum, incidence angle and inverter efficiency or any further influence to be considered.

2 METHODOLOGY AND DATASETS

In order to evaluate the different models, first a questionnaire survey was carried out to define the boundaries of the modelling round-robin (RR). The main aim of the questionnaire was to gain an understanding of each model as well as to identify the input requirements and output information.

The RR was then carried out by giving each centre 2 years of data for 5 different PV modules from 3 locations. Table **II** lists these modules with information about their location and main STC values. The data sets available do not allow a spatial translation, as this would require identical modules to be operated at all the different sites. Some such candidates exist (in the initial stages of measurements) but for this paper, the data consistency could not be ensured. It is expected that such data will be measured in a future integrated project and further RRs are planned.

Each centre was sent the data for the first year including environmental and PV electrical measurements. The data for the second year was limited to environmental measurements only, for the purpose of the simulation of a blind RR.

The 3 sites chosen provide a good representation of the climatic conditions experienced in Europe. Figure 1 demonstrates the distribution of the irradiation available at each site and highlights the spread of energy associated with different irradiance levels.

Module Generic Name	cSi_1	cSi_2	cSi_3	CIS	aSi-2j_
Location	A	B	C	C	A
Latitude	43°39	51°06	46°01	46°01	43°39
Pmax /W	105	36.15	100	40	40
Temp.Coeff (Pmax)/%C	-0.43	-0.44	-0.47	-0.6	-0.22
Eff/ %	11.7	14.5	12.1	9.4	5.3

Table **II** : PV modules with their STC values. A= Cadarache, F; B= Wroclaw, Pl; C= Lugano, C.

The overall energy is the highest in Cadarache which is situated at a much lower latitude than Wroclaw, with Lugano somewhere in the middle. It is surprising that the absolute amount of energy in the lower end of the spectrum (<200 W/m^2) does not vary significantly between the different sites, but there are noticeable differences in the high irradiance part (>600 W/m^2).

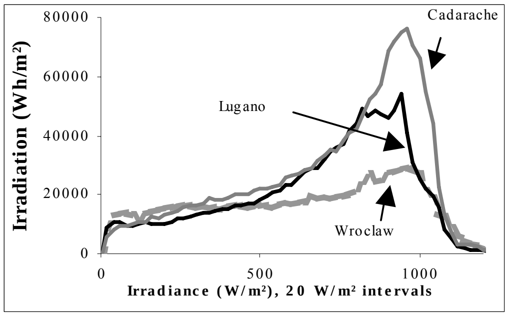

Figure 1: Frequency distribution function of the incoming energy

Each modelling method required certain input parameters, which are listed in Table III. Where the parameter was not measured or the method required it to be calculated this calculation was done by the particular institution.

Environmental Inputs	Matrix	MOTHER PV	Module Back Temp.	On-Line Simulator	SSC
Ambient Temperature	X			X	
Device temperature		X	X	XC	X
Irradiance in plane (POA)	X	X	X	XC	X
Irradiance horizontal				X	X
Spectral information					X

Table **III**: Environmental inputs required by each model XC means the variable will be calculated.

3 RESULTS

Each centre carried out their own standard data-treatment, which resulted in the rejection of some measurements. These measurements were considered to be flawed for one reason or another; it could happen that simple correction for outliers resulted in the exclusion of these points. This exclusion of some of the data points results in different annual integrated solar irradiation used by different groups. This difference is shown in Figure 2 for each module dataset, relative to the average.

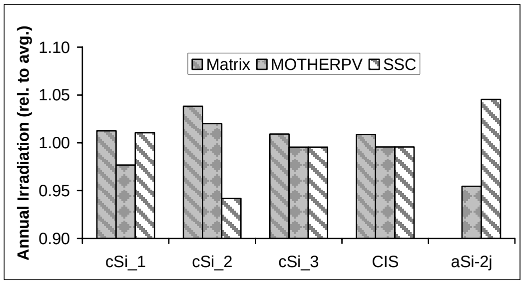

Figure 2: Shows the difference in annual integrated solar irradiation used by each modelling group, introduced through variations in data handling. Data shown relative to the average for each module.

The knock-on effect is a difference in the measured energy production (electrical kWh/kWp) used as a base line for the models (in year 1 this varies by as much as 9%, showing that data treatment for different modelling approaches is a critical consideration). This variation is very significant in the context of this work, as this is broadly speaking the error margin of the different methods.

The first task of the RR was to identify how accurately the energy production could be re-calculated for the base line year, i.e. the year where the electrical data was used for the calculation. This is not an independent test but represents the best case scenario. Figure 3 shows the error during this characterization year between the measured and modeled energy yield.

It might be expected that the errors arising from this same-year consistency check would be low. This is generally the case, but with a noticeable difference between the SSC and On-line Simulator and the other models. At this stage of the project, the precise reason for such difference is not clear. Possible factors, to be investigated, are the nature and impact of data treatment, and the reliance on STC data (not used in the other models).

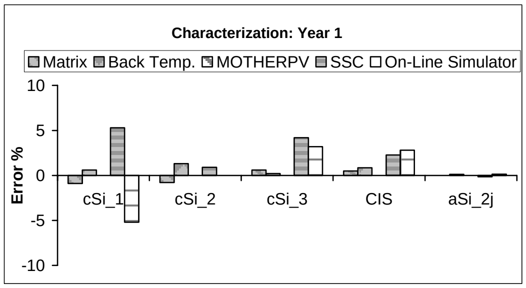

Figure **3**: Shows the error between the measured and modeled energy yield for year 1 dataset from the difference centers.

The a-Si_2j device had been operating for more than 6 months prior to the data used here, hence initial degradation had already occurred and more or less stable performance is observed in the data used for the RR. The matrix method was not applied to this module, as it has not yet been characterized through the required laboratory measurements.

Surprisingly, the highest errors occur for the c-Si devices and specifically the SSC and online calculator methods have noticeable deviations, for different reasons.

The On-line Simulator is based on ambient temperature and horizontal irradiance, while the other models are based on module temperature and in-plane irradiance. This introduces further steps in the modelling, which will result in larger error margins. Furthermore, the calculations introduce some approximation (e.g. thermal mass of a module), which will introduce further complications. Given these additional steps, the results of the simulations are actually very close to the measured energy production.

The reasons for the over-prediction of SSC method are explained by the model requiring spectrally corrected irradiance values for the determination of the temperature coefficient and for the irradiance dependence of the module performance. However, no spectral data was available for the modelling, thus the spectral losses were not calculated and the assumption of a constant spectrum will result in an overestimation of the device performance. Furthermore, only low angles of incidence are considered when extracting the device performance coefficients, again resulting in an overestimation of the device performance. In the other models, these effects are merged with irradiance and temperature, increasing the accuracy for limited environmental datasets but decreasing the possibility of separating these physical effects, which may become important for translation to different locations. The data for modules cSi_3 and CIS did not include short-circuit current measurements and so the approximation was made that I_{SC} and I_{MPP} have identical dependence on irradiance magnitude and spectrum, which introduces further error sources.

The methods MOTHERPV, Module Back Temperature and Matrix handle all modules well. The MOTHERPV model specifically has virtually no error, which is largely due to the input data being identical to the one used for the calculation of the energy output.

The methods MOTHERPV, Module Back Temperature and Matrix can all reproduce the energy yield to an accuracy that is in the order of magnitude of the measurement accuracy.

In the second step, a temporal translation was carried out, i.e. the year to year variation. Only the environmental data supplied from the second year of data was supplied to the modelling teams, with the measured electrical data held back to validate the blind modelling results. Typically, the error doubled for most methods. This is still within reasonable accepted errors as seen in Figure 4. It is apparent that the easiest module to predict in the same-year calculations, the aSi_2j module, exhibits significant overestimation of energy production for all the approaches. This illustrates the difficulties in predicting energy yields for thin film devices. The error obtained for the c-Si devices is typically less than 8%. The On-line Simulator experienced some difficulties with the module data from Wroclaw, Poland. The reason for this is that the horizontal irradiance does not translate well into the inclined irradiance and a constant tilt was assumed over the year while the tilt actual changed twice over the year. For this reason no results are presented here.

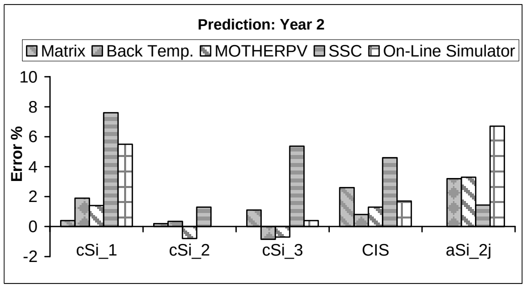

Figure 4 : Shows the error between the measured and the predicted energy yield for year 2 dataset from the difference centers.

As in the previous example, the SSC model over-predicts the energy production for all devices, for the reasons explained above. What is surprising is how accurately it predicts for aSi_2j, which can be explained by the fact that the spectral correction carried out was originally developed for a-Si devices and is most valid for large band gap devices. The precise effect of the spectrum is very much device dependent; even within categories such as c-Si it can be very significant, depending on the blue response of the device. It is clear from these results that this needs further improvements.

The three methods Matrix, Online Simulator and SSC are consistently overestimating the yield, indicating that some losses are not considered. Matrix, MOTHERPV and Module Back Temperature can predict the output with an accuracy of better than 3%.

4 CONCLUSIONS

A round robin assessment of the different modelling approaches was successfully completed for temporal shifts in performance at a given site. This work will later be extended to include spatial variations, although currently there is not enough data available for such an assessment.

Key factors pertinent to the organization of such projects, which have come to light during this work, include: that careful attention must be paid to the format of data for distribution (consensus is needed in identifying the most appropriate). The database structure is of utmost importance (it must be flexible enough to cope with the different modelling approaches, but simple and user-friendly). It was demonstrated above how different filtering procedures (i.e. removal of outliers or suspect data) affect the modelling outcomes - an arrangement must be made as to how the data should be filtered and handled or this must be done beforehand and only filtered data issued to truly standardize the dataset used by each project partner.

The performance of the models investigated overall is very high, with an advantage evident for the empirical models that do not attempt separate the different environmental effects of irradiance, temperature and spectrum. This is not unexpected, since the operational environment is similar and if any computational deficiencies exist, these are likely to be apparent from site to site comparison. Errors will be larger if only the STC module rating is available or to a lesser extent if the operational data is limited. Errors would also increase if the same module was not used throughout, due to module to module variation. Specifically, further round robin tests are planned to deal with site to site translation and calculations based on representative modules. It is also planned to extend the range of computational approaches to be assessed.

Further details of the project can be found at: http://www.pvcatapult.org/

5 ACKNOWLEDGEMENTS

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6 REFERENCES

1. Ransome, S.J. and J.H. Wohlgemuth. *Understanding and Correcting kWh/kWp Measurements*. in *PV in Europe*. 2002. Rome.
2. Gottschalg, R., et al. *Translation and validation of Laboratory Measurements of Amorphous Silicon Devices to Real Operating Conditions*. in *17th European Photooltaic Solar Energy Conference*. 2001. Munich.
3. Raicu, A., et al. *Annual and Seasonal Energy Rating of mon-Si, a-Si and GaAs Test Cells for the USA by the RRC Method*. in *IEEE PVSC*. 1991.
4. Kenny, R.P., et al. *ENERGY RATING OF PV MODULES: COMPARISON OF METHODS AND APPROACH*. in *WCPEC*. 2003. Osaka, Japan.
5. Anderson, D., T. Sample, and E.D. Dunlop. *Obtaining Module Energy Rating From Standard Laboratory Measurements*. in *17th European Photovoltaic Solar Energy Conference*. 2001. Munich, Germany.
6. Williams, S.R., et al. *MODELLING REAL ANNUAL PV MODULE PERFORMANCE WITH CONSIDERATION TO SPECTRAL AND INCIDENCE ANGLE EFFECTS*. in *19th European Photovoltaic Solar Energy Conference*. 2004. Paris, France.
7. Marion, B., *A method for modeling the current-voltage curve of a PV module for outdoor conditions.* Progress in Photovoltaics, 2002. **10**(3): p. 205-214.
8. Kroposki, B., et al., *Comparison of Photovoltaic Module Performance Evaluation Methodologies for Energy Ratings.* Conference Record of the IEEE Photovoltaic Specialists Conference, 1994. **1**: p. 858-862.
9. King, D.L., W.E. Boyson, and J.A. Kratochvil. *Analysis of Factors influencing the Annual Energy Production of Photovoltaic Systems*. in *29th IEEE PVSC*. 2002. New Orleans.
10. Guerin de Montgareuil, A. *An Emperical Synthetic Law Between the Modules Energy Output and the Meteorological Data*. in *3rd WCPEC*. 2003. Osaka, Japan.
11. Orgill and Hollands, Solar Energy, 1977. **19**.
12. Perez, R., et al., *Modeling Daylight Availability and Irradiance Component from Direct and Global Irradiance.* Solar Energy, 1990. **44**(5): p. 271-289.
13. Van Dijk, V., *Hybrid photovoltaic solar energy systems, design, operation, modelling, and optimisation of the Utrecht PBB system*. 1996, Utrecht University.