INTERCOMPARISON OF DIFFERENT ENERGY PREDICTION METHODS WITHIN THE EUROPEAN PROJECT "PERFORMANCE" - RESULTS OF THE 1ST ROUND ROBIN

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ABSTRACT: Eight separate energy prediction methods, developed independently across European Universities and Research Centres, have been compared with respect to their estimated DC energy generation for five different photovoltaic (PV) module technologies and 7 different sites distributed over whole Europe. The analysis of this work is the basis for further improvements of each of the modelling approaches and thus enables a reduction of the prediction error in PV yield estimations.
The recently completed first of three planned round-robin inter-comparisons found that the agreement for all methods and all technologies is within ±5% on an annual basis, provided that the environmental parameters incident irradiance and the module temperature are well described. This good accuracy was also found when translating the energy yield measured at one location in Europe to another for an identical module utilising shorter time periods (months). Significantly higher errors were found when using different PV modules of the same manufacturer and technology to predict the energy yield at other sites. Here the variation in module power rating dominated the results of the energy prediction methods and a correction for these differences had to be applied.
Keywords: PV Module, Modelling, Energy Rating

1 INTRODUCTION

The Energy Rating of a PV module or system is one of the most important pieces of information for an end-user. It helps the installer to guarantee a certain output which then can be verified by the end-user. This enables to choose between different products and solutions.

There are currently a number of energy prediction methods under development in Europe. Extended round robin tests (RR) to compare and validate these methods for the entire range of operating conditions across Europe are therefore very important. These inter-comparisons are part of the European project PERFORMANCE [1]. The work is split into different phases in which the complexity of the round robins is increased continuously, by adding gradually the results generated within the other work-packages of the Performance project, which are related to specific problems such as environmental effects (spectral, angle of incidence, etc), power degradation/recovery cycles, inverter performance, etc.

The first RR has recently been concluded and the second is currently under preparation.

2 ROUND ROBIN APPROACH

The first round robin has been concentrating on the energy prediction of single PV modules. This RR test uses sets of monitoring data (1-10minute resolution) of different module technologies (cSi, aSi, CIS, CdTe) measured at different sites of various European test-laboratories (ZSW-DE, INES-FR, ISAAC-CH, CREST-UK, ECN-NL, Solarlab-PL, Helsinki-FL).

For some modules some short period data (maximum 1 month) from different sites were available. One year data were available from different laboratories but not of the same modules as for the shorter period but only of modules of the same type (same id-code).

For each module type one complete data set (i.e. meteorology and electrical measurements) was distributed to the eight participants for the extraction of the module parameters needed to predict the energy for any site. For the energy prediction inter-comparison only the module temperature and incident irradiance measured by a pyranomter was given as input. With these - according to the lengths of the data sets - the daily, monthly or annual energy output of the single modules had to be predicted.

In this way, it is possible to verify the transferability of module parameters determined for one site to another site. Furthermore, the transferability from one module to another (same module typology) is investigated.

The simplified approach of considering only module temperature and incident irradiance measured by a pyranometer instead of the ambient temperature and horizontal irradiance as used by common simulation programs, aims to reduce the error sources to a minimum. In this way the accuracy of the single energy prediction methods is determined on their own and the more detailed investigation of predicting the operating environment can be investigated separately. The next RR will be used to introduce the different spectral and angle of incidence models and to compare and validate them.

3 ENERGY RATING METHODS

Table I shows the modelling methods evaluated and applied in this work, the groups developing and operating them are given as their main reference. A total of eight methods were analysed within the first round robin. At this stage, only methods able to handle single module data could be considered. Some partners slightly adapted their methods to work with the given input parameters.

The methods are characterised by their determination of either the real operating efficiency η or power P of a module at various environmental conditions. They are therefore easily comparable since one term can be easily transformed to the other by applying the following equation $P = \eta \cdot A \cdot G$ (A indicates module area, G describes the incident irradiance). The main differences between the methods are the ways to handle the input data, the execution of the single steps and the fit equations used.

Table I: List of Energy Rating methods reviewed in this RR with the groups operating them, their main equations and references.

name of method	from	Ref	power or efficiency equations	temperature coefficient(s)
SSE	CREST	[2]	$\eta(G,25°) = C_0+C_1G+C_2\ln G$	TC@1000W/m²
Yield Simulator	ECN	[3]	avg $\eta(G,25°)$	average TC (250,500,750,1000W/m²)
Somes	UU	[4]	$P_t = P_{nom} \cdot \frac{\Theta(G)}{\Theta(1000)} \cdot \frac{G}{1000}$	TC=0.4%/°C (default value)
MotherPV	INES	[5]	avg $\eta(G,25°)$	TC(G)
PV-SAT	H2M	[6]	$\eta_{MPP}(G,T) = a_1 + a_2G + a_3 \ln(G*m^2/W) \cdot (1+\alpha \cdot (T-25))$	
Matrix method	SUPSI	[7]	$I_m = I_{m,stc} \cdot G/1000 \cdot [1+\alpha_{Im} \cdot (\Delta T + T - 25)]$ $V_m = V_{m,stc}+C_0 \cdot \ln(G/1000)+C_1 \cdot (\ln(G/1000))^2+\beta_{Vm} \cdot (\Delta T+T-25)$	
ESTI-ER	JRC	[8]	$P(G,T)= I_{m,stc} \cdot G/1000 \cdot [1+\alpha_{Im} \cdot (T-25)] \cdot (V_{m,stc} + C_0 \cdot \ln(G/1000) + C_1 \cdot (\ln(G/1000))^2 + \beta_{Vm} \cdot (T - 25))$	
ZENIT	ISE	[9]	$P(G,T) = a \cdot G^2 + b \cdot \log(G+1) \cdot G + c \cdot \left(\frac{(\log(G+e)^2)}{G+1} - 1 \right) \cdot G + d \cdot (T-25)$	

The methods can be divided into two groups. Group one (CREST, ECN, UU and INES) determines separately, the module efficiency (for 25°C and different irradiance levels) denoted as $\eta(G,25°C)$ and the temperature coefficient as a constant TC or a curve TC(G) and treat these effects as independent of each other. The second group (SUPSI, JRC, H2M and ISE) describes the whole power surface P(G,T) or $\eta(G,T)$ as a single equation. Table 1 summarises the main equations of the methods.

The differences within Group 1 are related to how the efficiency curve at 25°C is extracted from the raw data and the value of the temperature coefficient used for the temperature correction. CREST describes the efficiency curves by the equation $\eta(G,25°) = C_0+C_1G+C_2\ln G$. The other three groups (ECN, UU and INES) apply a statistical approach with no fitting, where the curves are averaged from the measured raw data. The MotherPV method of INES is also different in that it does not use a time series as input for its energy calculations but a statistical distribution of irradiation profiles (energy received as a function of irradiance level) and module temperature profiles (average operating module back temperature as a function of irradiance level). The latter method is also the only method in group1 using irradiance dependent temperature coefficient and not a single value.

In Group 2, two methods are based on almost the same set of equations, with a slight difference in the approaches used to fit the equations. SUPSI fits I_m and V_m separately then calculates P_m, while JRC fits P_m directly. In the variant 1 of SUPSI's method, an additional parameter ΔT was introduced, which describes the difference between back of module temperature and cell temperature. In both cases, the equation used within the matrix method has six parameters, four of which can be determined from data sheet values or otherwise require indoor measurements. SUPSI determines all six parameters from fitting of raw data. JRC determines I_m and V_m in two different ways. One way is to calculate I_m and V_m by a fit to the raw data, giving a set of values for all the parameters in the equations which is, valid only for the given module. The other way is to determine $I_{m,stc}$ and $V_{m,stc}$ (or $P_{m,stc}$) separately by fitting and then use published values for C_0, C_1, α and β. The third member in this group, ISE, fits the entire power surface P(G,T), but with a slightly different equation based on four parameters only. H2M works with the same equations as CREST, but with a different data handling approach.

These differences explains why each partner extracts slightly different temperature coefficients TC and module efficiency curves $\eta(G,25°C)$ for the same set of data. Figure 1 shows an example of efficiency curves for a c-Si module. The temperature coefficients varied from 0.40 to 0.52 %/°C. For Group two the information had to be extracted from the determined power surface. The observed discrepancies explain the final difference in predicted kWh's in between the RR participants. It also highlights that the data management and the data cleaning is of as important to a good energy rating as the actual set of underlying mathematical models.

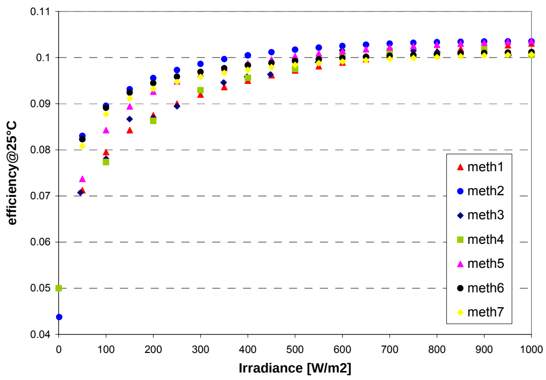

Figure 1: Efficiency curves at 25°C of a c-Si module extracted from real outdoor data by applying 8 different procedures.

4 ROUND ROBIN RESULTS

4.1 Same module measured for a short period at 4 sites

Four different module technologies were here investigated (sc-Si, mc-Si, CIS, 3j a-Si). The modules were measured at 4 different sites (Cadarache, Wrocław, Petten, Loughborough) for a time ranging from one to four weeks. The data from the first site, Cadarache, were used to characterise the modules. For the other sites the energy had to be predicted. Only the environmental data (time, incident irradiance and module temperature) were distributed. The energy predicted by each partner was then compared to the real measured energy. The following paragraphs show the results for each technology. One method (meth8) differs form the others due to the use of some standard c-Si values instead of extracting them from the Cadarache data, thus leading an off-set error. These data are therefore considered as not representative for this test and were not included in the final average error. Not all predicted the energy for the thin film technologies, as thei model was not developed for this.

Mono-crystalline silicon module

Figure 2 shows the results of the sc-Si module. For Wroclaw and Petten the predicted energy was on average 1.6% lower than the measured energy. There was a slightly higher error, 4.1% on average, for the translation to Loughborough. This is the site with the highest discrepancy to Cadarache meteorological conditions and with the shortest measurement campaign. All methodologies led to an under-estimation of the energy ranging from a 0.5% to a maximum of 6.5%. The average of all 3 sites is of 2.5%.

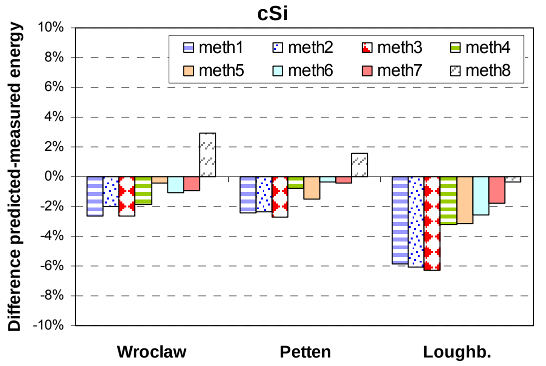

Figure 2: Error of single energy predictions methods for the sc-Si module.

Multi-crystalline silicon module

The errors for the mc-Si are similar to the one of the sc-Si module. The site to site translations led to a general underestimation of up to 4%, independt from site and month in which the module was measured. More precisely, the errors for Wroclaw and Loughborough are around 3% and for Petten, a little lower, around 1.8%. The average under prediction for the site to site translation of the mc-Si module is of 2.6%, almost the same as the one of the sc-Si module.

CIS module

Figure 3 shows the results of the CIS module. The results confirm the general trend to under-predict the energy production, when translating the data to another site. It seems to be independent of applied methodology, site and month of the prediction, but the error is visibly increased for all approaches. The errors range here from 3-7% with an overall average of 4.7%.

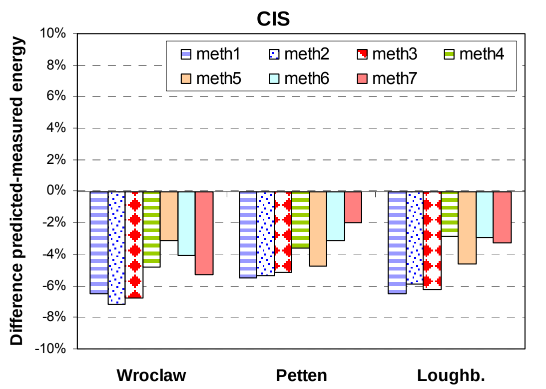

Figure 3: Error of single energy predictions methods for the CIS module.

a-Si module

Figure 4 summarises the results of the amorphous silicon module. The technology dependent changes in STC power during outdoor exposure, caused by the Staebler-Wronsky degradation and thermal annealing, must be considered when investigating energy prediction. Due to the module not continuously being exposed at one place, but being moved throughout Europe with periods of dark storage during the transfer, the modelling of these effects could not be done. Despite this difficulty, the error was still within ±5%, but with a clear seasonal variation dependent on the period in which the measurements were made (spring/Cadarache, summer/Wroclaw, late summer /Petten, autumn/Lougborough). Spectral dependencies, have not been considered at this stage as the essential input – measured spectra – do not exist for these data sets. These will only be introduced within the next round robins.

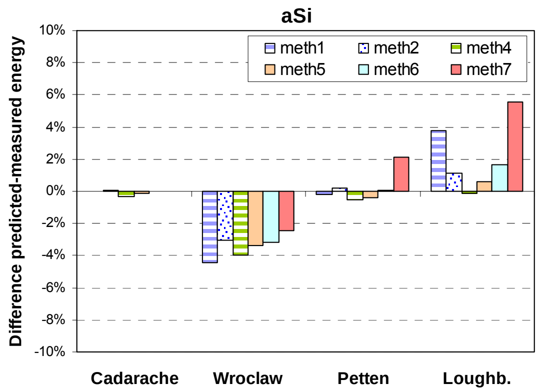

Figure 4: Error of single energy predictions methods for the a-Si module.

4.2 Same module type measured for 1 year in 2 sites

The main difference to the approach described before, is that the annual output is validation and that the module for which the energy is to be predicted is only of the same type as the source module (id code), but not exactly the same. Differences in module performance have to be considered. Due to the time span being much longer than in the previous case (4.1), the capability of the models to reproduce the data of the originally used site is shown as well. In the earlier case the error was almost negligible. Three different technologies are investigated (mc-Si, CIS and CdTe).

mc-Si module (Cadarache → Lugano)

Figure 5 shows the errors in annual energy prediction obtained by the different institutes for a poly-crystalline silicon module. The simulation of the Cadarache data led in all cases to an under-prediction in annual energy production of 0% to 2.6%, with an average of 1.2%.

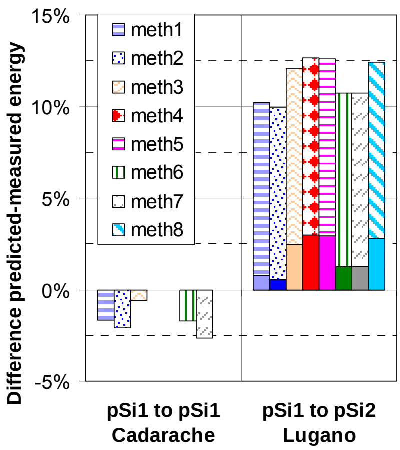

Figure 5: Error of the annual energy prediction with 8 different methods for a mc-Si module

The translation to another site, here Lugano, leads of course, if no information is given about the real rating of the module, to an error which is the sum of the simulation accuracy plus the error due to the differences in module performance. The total error is represented in Figure 6 by the patterned bars. An over-prediction of 11.1% is observed on average, which is reduced to an error of only +1.6% (represented by the filled columns), if the energy is corrected by considering the difference in STC power of the two modules (8.6%).

The monthly representation of the errors for Cadarache, illustrated in Figure 6, shows that the winter months are the most problematic to predict. An under-prediction of up to 8% is observed. All methods under-predict the energy even if no site to site or module to module translation is done at this stage. The error trend over the year is the same for all methods, with just a small offset amongst them. This graph shows clearly that there is potential for further improvements and this will be investigated in the next round robins. The possible reasons for this behaviour are relatively low operating temperature, high angles of incidence and spectrum with a red hue.

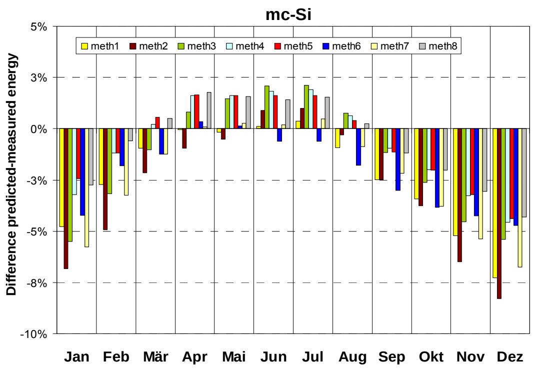

Figure 6: Monthly energy prediction accuracy of the module measured at Cadarache for 8 different prediction methods.

A preliminary test made with one of the methods showed that the use of the module short circuit current as self reference for the irradiance determination instead of the pyranometer values, leads to a significant improvement in the monthly energy predictions (see Figure 7). This confirms, as expected, that the quality of irradiance, i.e. reflection losses and spectral effects, has to be considered as next.

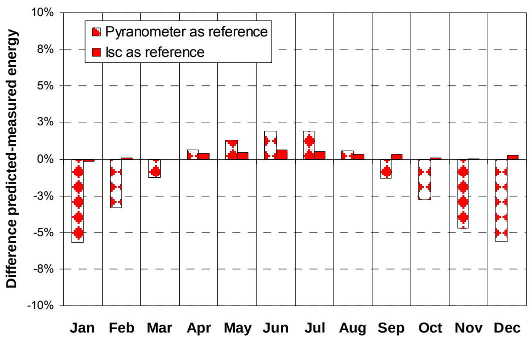

Figure 7: Monthly energy prediction accuracy of a mc-Si module by applying either pyranometer data for irradiance or the module short circuit current as self reference.

CIS and CdTe modules (Widderstall → Helsinki)

The data of the modules measured in Widderstall were first translated to a second module measured at the same site and then to two other modules installed at another site with very different climatic conditions (Helsinki). Data with snow coverage were identified and removed.

After correcting for differences in STC power, the errors of the three CIS modules were all in line with those of the CIS module analysed before. The errors are between -1.5% and -6.5%, with an average of -3.5%. No clear difference between the pure module translation and the translation to another site is visible.

For the three CdTe modules the correction led to an under-estimation of -4.4% with errors up to almost 10%. The simple STC correction is probably not precise enough for these modules, due to significant differences in the overall performance.

5 OUTLOOK: USING ADDITIONAL MESURES FOR THE MODELL QUALITY

Up to now, only the 'mean bias error' MBE of the modelled energy gain is used for the comparison of the models. For a more comprehensive analysis of the model performance, additional error measures may be taken into account. Whereas the mean bias error gives information on a general offset of the model results, the measure 'root man square error' RMSE gives additional information on the general scatter of modelled versus measured data.

As a third measure the 'Dispersion' may be used (see e.g. [10]). The dispersion is defined by:

$$disp = \sqrt{2\sigma(P_{pred})\sigma(P_{meas})(1 - r(P_{pred} \cdot P_{meas}))}$$

P_{meas} : masured power output

P_{pred} : predicte power output

$\sigma(P_{meas})$: standard deviation of P_{meas}

$\sigma(P_{pred})$: standard deviation of P_{pred}

$r(P_{meas}, P_{pred})$: correlation coefficient of P_{pred} and P_{meas}

Given similar values of the MBE and the RMSE, the dispersion gives information on how much the relation of predicted and measured values diverges from a linear relation. Low values of the dispersion indicate, that the MBE and the RMSE can be reduced by simple linear corrections of the prediction. High values of the dispersion indicate that a reduction of the errors call for non linear corrections.

An example for the combined analyses of this three error measures is given in Table II. For the test performed for one of the c-Si modules, the three measures are determined for 6 different data sets. It has to be remarked, that for this example, all measures are very close, as discussed above. In the following table the methods are ranked according to the dispersion value (first column). The subsequent columns give the values for the MBE and the RMSE together with the ranking according to that measure. Partly all three measures give a similar ranking for a method (see e.g. meth4), partly the rank is quite different for the three measures (see e.g. meth3; meth8a). According to the dispersion, one may expect, that the e.g the results for method 3 concern the MBE and the RMSE may be improved remarkably by a simple linear correction. For method 8b however, the removal of the bias error will call for more efforts, due to the indication of nonlinearities in the relation of the prediction to measured data indicated by the increased value of the dispersion.

Table I: Ranking of dispersion, MBE and RMSE error of a c-Si module simulated with different energy prediction methods.

method	disp [W]	MBE		RMSE	
		Value	rank	value	rank
meth4	1,5246	-0,0079	1	0,0585	2
meth3	1,5309	-0,0269	7	0,0640	5
meth8a	1,5333	-0,0117	2	0,0652	6
meth5	1,5336	-0,0148	3	0,0669	7
meth2	1,5438	-0,0238	6	0,0634	3
meth1	1,5767	-0,0200	5	0,0634	4
meth8b	1,5787	0,0151	4	0,0576	1

Based on this first example a scheme for a comprehensive evaluation and ranking of the model quality will be applied in subsequent RR schemes within PERFORMANCE.

6 CONCLUSIONS

1. The results of this RR show that the use of only two input parameters, the module temperature and in-plane irradiance measured by a pyranometer, produce good results for all technologies with uncertainties in the range of ±5%.
2. The use of Isc instead of the irradiance measured by a pyranometer further reduces the annual error prediction accuracy, due to a significant improvement for the winter months. It will be therefore important within the next RR to validate the existing approaches to model the effective irradiance.
3. The energy predictions of similar modules but with different STC power led to the highest errors, due to the differences in individual performance..The knowledge or estimation of these differences is therefore crucial for an accurate energy prediction.
4. The amorphous silicon technology is the most difficult to predict due to the seasonal changes in STC performance and spectral dependencies. However, the energy predictions led to astonishingly good results of ±5% for all approaches.
5. All energy prediction methods showed similar results, which does not allow for any preferred selection at this stage.

6 REFERENCES

[1] C. Reise, G. Ebert, M. Köhl, W. Herrmann, D. Stellbogen, N. Pearsall, R. Gottschalg, H. de Moor, E. Despotou, E. Dunlop, “PERFORMANCE - a science base on PV performance for increased market transparency and customer confidence”, Proc.21 PVSEC, Dresden, Germany (2006)
[2] A. Raicu, et al, “Annual and Seasonal Energy Rating of mono-Si, a-Si and GaAs Test Cells for the USA by the RRC Method”, IEEE PVSC, (1991).
[3] http://www.ecn.nl/solar/yield/index2.html
[4] Dijk, V.A.P. van, E.A. Alsema - SOMES version 3.0; Technical Reference Manual – Report 92009, Department of Science, Technology and Society, Utrecht University, Utrecht (1992).
[5] A. Guérin de Montgareuil, “Description of MOTHERPV, the New Method Developped at INES / CEA for the Assessment of the Energy Production of Phovoltaic Modules”, PVSEC22, Milan, 2007
[6] H.G. Beyer, et al, “Identification of a General Model for the MPP Performance of PV-Modules for the Application in a Procedure for the Performance Check of Grid Connected Systems”, 19th EUPVSEC, Paris (2004).
[7] „Final Report 2000-2003: Qualità e resa energetica di moduli ed impianti fotovoltaici - centrale LEEE-TISO”; SFOE contract n. 36508.
[8] R.P. Kenny, G. Friesen, D. Chianese, A. Bernasconi, and E.D. Dunlop, “Energy Rating of PV modules: comparison of methods and approach”, Proceedings of the 3rd World Conference on Photovoltaic Solar Energy Conversion, Osaka, (2003).
[9] B. Müller, personal communication, model still under development.
[10] M.Lange, Analysis of the uncertainty of wind power redictions.PhD thesis, University of Oldenburg (2003)

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