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### ► To cite this version:

Íñigo Pagola, Martín Gastón, Carlos M. Fernández-Peruchena, Jose Luis Torres, Manuel Silva, et al.. Comparison and fitting of several Global-to\_beam irradiance models in Spain. 15th SolarPACES Conference, Sep 2009, Berlin, Germany. pp.11724. <hal-00919947>

**HAL Id: hal-00919947**

**<https://hal.science/hal-00919947v1>**

Submitted on 17 Dec 2013

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# COMPARISON AND FITTING OF SEVERAL GLOBAL-TO-BEAM IRRADIANCE MODELS IN SPAIN

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## Abstract

In this paper, a comparison of different global to beam irradiance models has been performed. In a first step, five global-to-beam irradiance models are compared against ground measurements from three sites in Spain. Four of these existing models have also been fitted in the selected sites, and the results are presented as well. Finally, one new model (fully described in paper 11693) is also compared with the same ground measurements. The model comparison has been made by means of first and second order statistics, as RMSE and some parameters based on Kolmogorov-Smirnov test. The comparison of the beam irradiance provided by the models with the measured beam irradiance shows a similar behavior of the existing models in the selected Spanish sites. The four new fitted models show a better behavior related to the first order statistics, but the fitted models do not provide appropriate results when the irradiance is very high. The results provided by the new developed model seem to be better than the others. As it is a first approach, these results confirm that the applied methodology is appropriate for this objective, and it will be further developed in future works.

Keywords: global and beam irradiance, model comparison, solar radiation.

## 1. Introduction

Nowadays, there is a growing need of data related to beam solar radiation. The market situation of solar technologies and the premium prices in countries as Spain, leads into the need to characterize the expected beam solar radiation in a specific location by means of a short measurement campaign. To estimate beam radiation from global radiation, information derived from satellite images or data from well known data bases of global solar radiation can be used. In both cases, global-to-beam irradiance models are often needed.

In this work, the results provided by five global-to-beam irradiance models are compared against ground measurements from three sites in Spain. Another four new global-to-beam irradiance models have also been fitted with the measured data in the selected sites, and the results are presented as well. The first approach to a new model and the results provided for the same locations are also compared.

This study follows the line proposed by Ineichen [1] showing the accuracy that can be expected from the most commonly used models for estimating beam solar radiation, and it also proposes local fitting of this models as a first way to improve the accuracy.

## 2. Methodology

Five models of global to direct beam irradiance have been selected for this study. These global-to-beam models are Orgill and Hollands model [2], Erbs model [3], Reindl model [4], Louche model [5] and Perez model [6]. The purpose of the present study is to do a comparison of the five models against measurements from three locations in Spain. The three Spanish locations selected are Madrid, Murcia and Cáceres. For this

comparison a Kolmogorov-Smirnov test has been applied to check whether the beam irradiance series provided by the models could statistically be similar to the measured data or not. Some statistical parameters based on the Kolmogorov-Smirnov test of first order (RMSE, Relative RMSE and BIAS) and second order (KSI and OVER) [7] have been also used. The KSI parameter (Kolmogorov-Smirnov test Integral) is defined as the integrated differences between the cumulative distribution functions of the two data sets. For the determination of the OVER parameter, the integration is only calculated for those differences between the cumulative distribution functions that exceed the critical limit of the original Kolmogorov-Smirnov test.

The original five global-to-beam models were developed using measured data in sites which are very far away from the selected Spanish locations. For this reason four new models have been derived from the measured data of global and beam irradiance in the Spanish locations. The formulation of these new global-to-beam models is similar, one by one, to the first four original models:

*Orgill and Hollands:*

$$k_d = \begin{cases} 1.0 - 0.249k_i & k_i \leq 0.35 \\ 1.577 - 1.84k_i & 0.35 \leq k_i \leq 0.75 \\ 0.177 & k_i > 0.75 \end{cases}$$

*Erbs:*

$$k_d = \begin{cases} 1.0 - 0.09k_i & k_i \leq 0.22 \\ 0.9511 - 1.1604k_i + 4.388k_i^2 - 16.638k_i^3 + 12.336k_i^4 & 0.22 \leq k_i \leq 0.8 \\ 0.165 & k_i > 0.8 \end{cases}$$

*Reindl:*

$$k_d = \begin{cases} 1.020 - 0.254k_i + 0.0123\cos\theta & k_i \leq 0.30 \\ 1.4 - 1.749k_i + 0.177\cos\theta & 0.30 \leq k_i \leq 0.78 \\ 0.486k_i - 0.182\cos\theta & k_i > 0.78 \end{cases}$$

*Louche:*

$$k_b = 0.002 - 0.059k_i + 0.994k_i^2 - 5.205k_i^3 + 15.307k_i^4 - 10.627k_i^5$$

But in this paper new coefficients are fitted for these four models. A model similar to the Perez model has not been fitted with measured data because of its complexity. Results provided by these new four models are also compared to the beam irradiance measured in the three Spanish locations.

One new model has been developed and the first approach to it is fully described in the paper 11693 “A new learning methodology of global-to-direct irradiance based on clustering and kernel machines techniques”. The results provided by this new model for the same locations are also compared in the present paper.

### 3. Data used for the global-to-beam irradiance model comparison

In this work, beam irradiance given by five global-to-beam irradiance models are compared to the measured one in some ground stations. The available data for the selected locations, Madrid, Murcia and Cáceres, are hourly data from October 2005 to September 2008.

To ensure the quality of the measured data several quality test have been applied to them. The quality tests which have been used are the ones recommended by the Baseline Surface Radiation Network (BSRN) in its Operations Manual [8]. These quality tests are the following:

- Physically possible.
- Extremely rare.
- Across quantities.

In addition, the extraterrestrial irradiance  $G_0$  has been calculated for each data, and the values of measured global irradiance which exceeded the corresponding extraterrestrial irradiance have not been used for the model comparison.

### 4. Results

Once the measured data have been filtered, the four new models, with similar formulation to the first four models but derived using the measured data in the three Spanish locations, have been fitted.

*Orgill and Hollands fitted:*

$$k_d = \begin{cases} 0.9818 - 0.5870k_i & k_i \leq 0.35 \\ 1.2056 - 1.3240k_i & 0.35 \leq k_i \leq 0.75 \\ 0.2552 & k_i > 0.75 \end{cases}$$

*Erbs fitted:*

$$k_d = \begin{cases} 0.9522 - 0.3119k_i & k_i \leq 0.22 \\ 0.6059 + 2.9877k_i - 10.5675k_i^2 + 10.1833k_i^3 - 3.0475k_i^4 & 0.22 \leq k_i \leq 0.8 \\ 0.3209 & k_i > 0.8 \end{cases}$$

*Reindl fitted:*

$$k_d = \begin{cases} 0.912075 - 0.676854k_i + 0.257310\cos\theta & k_i \leq 0.30 \\ 1.197462 - 1.268849k_i - 0.039263\cos\theta & 0.30 \leq k_i \leq 0.78 \\ 0.696484k_i - 0.489290\cos\theta & k_i > 0.78 \end{cases}$$

*Louche fitted:*

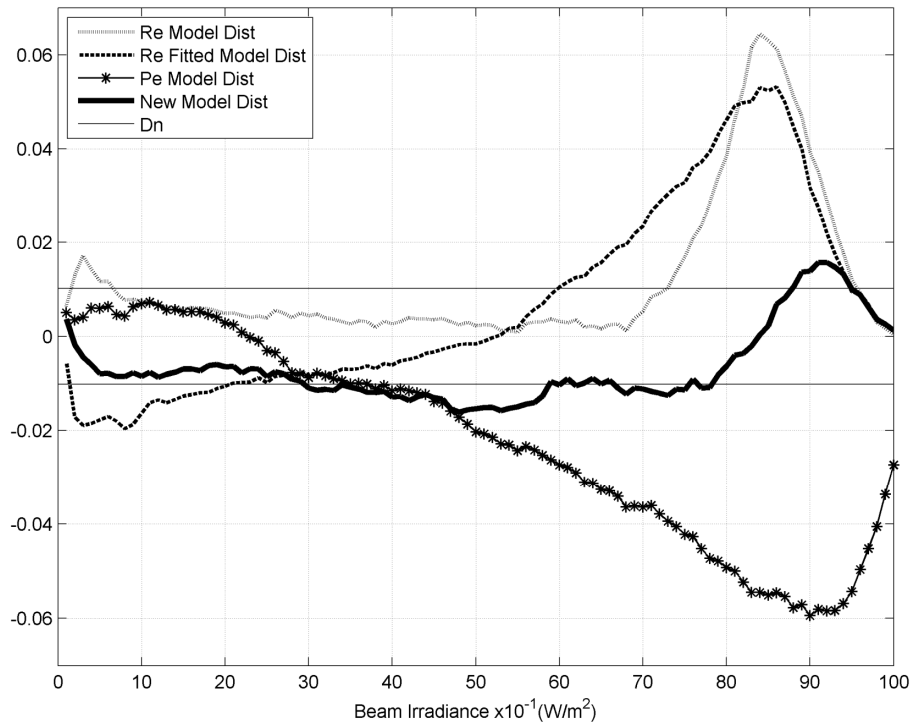
$$k_b = -0.0033 + 0.0888k_i + 0.3250k_i^2 - 1.6287k_i^3 + 8.4158k_i^4 - 6.9684k_i^5$$

In this paper can be shown the validation of the following models:

- Five global-to-beam existing models (Orgill and Hollands, Erbs, Reindl, Louche and Perez).
- Four existing models (Orgill and Hollands, Erbs, Reindl and Louche) but fitted with local data.
- A new model developed by CENER (described in the paper 11693).

For the validation of the models the results of the Kolmogorov-Smirnov test and some statistical parameters based on it are presented for each Spanish location.

Figure 1 and Table 1 show the results for the location of Madrid.



**Fig. 1. Kolmogorov-Smirnov test of Reindl, Perez and the new model for Madrid location**

As can be seen in Table 1, for Madrid location, the five original models present almost the same behavior in terms of the RMSE, being the Reindl model the one which gives better results. According to the second order parameters, the model which presents the best behavior for Madrid location is the Erbs model.

The four models similar to the first four original but fitted with data measured in the Spanish locations

improve the RMSE and BIAS parameters, but provide worse results for the second order parameters.

The new developed model presents a good behavior in Madrid location improving most of the analyzed parameters.

Statistical Parameter		MODELS					MODELS FITTED WITH DATA				NEW MODEL
Order	Name	ORGILL	ERBS	REINDL	LOUCHE	PEREZ	ORGILL	ERBS	REINDL	LOUCHE	
1 <sup>st</sup> order	RMSE	118	119	112	115	113	111	109	100	104	80
	rRMSE %	29	29	28	29	28	27	27	25	26	20
	BIAS	-9	-3	-12	12	23	-4	-4	-5	-4	7
2 <sup>nd</sup> order	KSI	11	10	12	14	24	16	17	16	17	10
	KSI %	103	96	118	137	237	156	165	159	169	95
	OVER	2.4	2.2	6.3	6.9	15.7	9.1	9.0	8.2	9.4	1.3
	OVER %	23	22	61	67	154	89	88	81	92	13

**Table 1. Statistical parameters of the different models for Madrid location**

Table 2 shows the results for the location of Murcia. As can be seen, for Murcia location, the five original models present almost the same behavior in terms of the RMSE parameter, and again the Reindl model provides better results for this parameter, and for the BIAS parameter as well. According to the second order parameters, the Reindl model presents the best behavior for Murcia location.

The four models similar to the first four original and fitted with data measured in the Spanish locations improve the RMSE parameter, but provide worse results for the rest of the parameters.

The new developed model presents a good behavior in Murcia location improving most of the analyzed parameters.

Statistical Parameter		MODELS					MODELS FITTED WITH DATA				NEW MODEL
Order	Name	ORGILL	ERBS	REINDL	LOUCHE	PEREZ	ORGILL	ERBS	REINDL	LOUCHE	
1 <sup>st</sup> order	RMSE	108	111	102	112	125	104	102	97	98	83
	rRMSE %	29	29	27	30	33	28	27	26	26	22
	BIAS	7	13	6	27	39	14	15	16	13	5
2 <sup>nd</sup> order	KSI	8	15	10	25	38	21	21	16	22	8
	KSI %	70	136	89	228	341	186	187	145	195	71
	OVER	1.8	7.0	1.5	15.8	28.2	10.7	10.7	7.1	11.5	0.2
	OVER %	16	63	14	142	252	96	96	63	103	2

**Table 2. Statistical parameters of the different models for Murcia location**

Table 3 shows the results for the location of Cáceres. As can be seen, for Cáceres location, the five original models present almost the same behavior in terms of the RMSE, being the Reindl model the one which gives better results for this parameter. According to the second order parameters, the model which presents the best behavior for Cáceres location is the Erbs model.

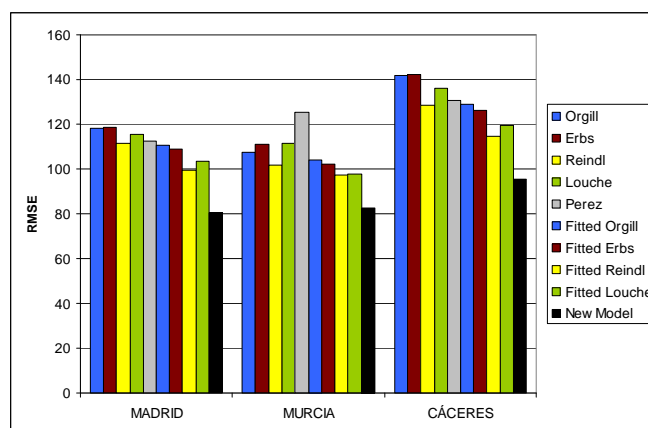
The four models similar to the first four original but fitted with data measured in the Spanish locations improve the RMSE parameter, but provide worse results for the rest of the parameters.

The new developed model presents a good behavior in Cáceres location improving most of the analyzed parameters.

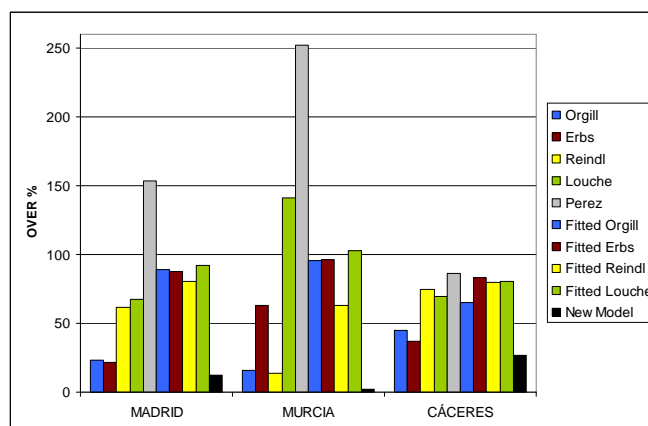
Statistical Parameter		MODELS					MODELS FITTED WITH DATA				NEW MODEL
Order	Name	ORGILL	ERBS	REINDL	LOUCHE	PEREZ	ORGILL	ERBS	REINDL	LOUCHE	
1 <sup>st</sup> order	RMSE	142	142	128	136	131	129	126	115	120	96
	rRMSE %	35	35	31	33	32	31	31	28	29	23
	BIAS	-10	-5	-19	9	11	-7	-9	-10	-9	9
2 <sup>nd</sup> order	KSI	15	14	19	17	18	14	15	17	15	13
	KSI %	128	120	169	148	161	123	136	152	135	114
	OVER	5.1	4.2	8.4	7.8	9.8	7.4	9.4	9.0	9.1	3.1
	OVER %	45	37	75	69	87	65	83	80	81	27

**Table 3. Statistical parameters of the different models for Cáceres location**

Next figures show a global view of the results for first and second order statistics. Figure 2 shows the statistical RMSE parameter and figure 3 the OVER % for the three Spanish locations and the five original models, the four fitted models and the new developed model. It can be observed that when the RMSE of the new fitted model are better than the original, the OVER % parameter increases for the original models fitted with measured data.



**Fig. 2. RMSE parameter for all the locations and models**



**Fig.3. OVER % parameter for all the locations and models**

## 5. Conclusions

Five global-to-beam irradiance models have been compared against ground measurements from three sites in Spain. The comparison of the beam irradiance provided by the models with the measured beam irradiance shows an inappropriate behavior of the existing models in the selected Spanish sites.

Four new models with similar formulation to four of the original ones have been fitted with the data measured in three Spanish sites. The four new global-to-beam irradiance models have been also compared against ground measurements. The comparison of the beam irradiance provided by the new fitted models to the measured beam irradiance shows a better behavior of the models, but the models do not provide appropriate results when the irradiance is very high.

There is a difference in the comparison related to the statistic parameters. If the first order statistics are compared, the new fitted models have improvements related to the existing ones, thus, the RMSE of the new fitted models are better than the original. But when second order statistics are compared the behavior is a little worse than the original models. The reason could be the data selected for the training, and in future works this possibility will be checked [9].

One new model has been developed and the results provided have also been compared with ground measurements. The results provided by the new developed model are better than the others, but as it is a first approach, it will be further developed. New formulation of global-to-beam models could be proposed so that they provide more appropriate results in the selected Spanish sites.

## Acknowledgements

This work was performed within the framework of the IEA SHC Task 36: Solar Resource Knowledge Management.

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