



HAL
open science

Long Term Estimation of DNI From Solar Global Irradiation. a Model to Estimate DNI From Monthly Clearness Index

Sara Moreno, Lourdes Ramírez, Carlos M. Fernández-Peruchena, Perez Elena, Ana Bernardos, Silva Manuel

► **To cite this version:**

Sara Moreno, Lourdes Ramírez, Carlos M. Fernández-Peruchena, Perez Elena, Ana Bernardos, et al.. Long Term Estimation of DNI From Solar Global Irradiation. a Model to Estimate DNI From Monthly Clearness Index. 16th SolarPACES Conference, Sep 2010, Perpignan, France. pp.277. hal-00919078

HAL Id: hal-00919078

<https://hal.science/hal-00919078>

Submitted on 16 Dec 2013

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

LONG TERM ESTIMATION OF DNI FROM SOLAR GLOBAL IRRADIATION.

A model to estimate DNI from monthly clearness index.

Sara Moreno¹, L. Ramirez², C. Fernández-Peruchena², E. Pérez¹, A. Bernardos² and M. Silva¹

¹ AICIA / Grupo de Termodinámica y Energías Renovables. Address: Avda. de los descubrimientos s/n, 41092 Sevilla (Spain). Phone: (+34) 954487233. Fax: (+34) 954 487233

² Solar Thermal Energy Department, National Renewable energy Centre (CENER). Address: C/ Isaac Newton n 4 -Pabellón de Italia, 41092 Sevilla (Spain). Phone: (+34) 902 25 28 00. Fax: (+34) 954 46 09 07

Abstract

In this work, the measurements of five meteorological stations sited throughout Spain are used to develop a model between monthly average beam irradiance and monthly clearness index. Then this expression is used to calculate monthly direct normal radiation from measured monthly horizontal global radiation data. This method can be applied to the extensive databases of horizontal global radiation values in order to study the long-time behavior of the direct normal radiation. After that, the accuracy of the model is evaluated with the recorded data of 16 different meteorological stations, also located throughout Spain. The Mean Bias Error and the Root Mean Squared Error obtained as function of the seasons and the different latitudes are evaluated. In addition, the results of all stations are compared with the monthly direct normal radiation obtained with a similar expression proposed by Ari Rabl[1] in 1981.

The results show how it could be possible to estimate monthly normal direct radiation values from monthly horizontal global irradiation measures assuming mean errors similar to the uncertainty of the measurement equipments.

Keywords: direct normal radiation, clearness index, global-to-beam models, monthly radiation data.

1. Introduction

The current Spanish legal framework, regarding solar thermal power plants, increases the interest in assessing long-term annual and monthly direct normal radiation distributions in different parts of the peninsula to estimate as accurately as possible the production expected with these types of technologies.

As there are few databases in Spain providing direct normal radiation for long periods of time, we have developed a correlation between monthly average beam irradiance and monthly clearness index. Therefore, we can use the extensive databases of horizontal global radiation to study the long-term direct normal radiation. For this purpose, we have mainly used the records (1999-2009) from stations belonging to the Spanish Meteorological Agency, AEMET, distributed throughout Spain.

2. Database

Solar radiation measurements used in this work to develop the model were recorded at five meteorological stations localized in different cities (listed in Table 1) distributed throughout Spain. The station located in Seville is found at the Engineering College of Seville, which is operated by the Group of Thermodynamics and Renewable Energies (GTER). The others four stations belong to the *Agencia Estatal de Meteorología* (AEMET). In every station, measurements have been validated by the BSRN recommended tests, represented and reviewed day-per-day. In this study, only those months recorded during the period 1999-2009 with 2 or less invalid days have been considered. The invalid days belonging to a valid month have been replaced with the average value of the daily normal direct radiation for this month.

Station	BdD	Latitude	Longitude	Valid months											
				Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec
Coruña	AEMET	43.37	-8.42	2	4	2	4	5	3	4	5	1	1	4	5
Madrid	AEMET	40.45	-3.72	7	6	7	6	5	9	8	7	7	5	7	7
Murcia	AEMET	38.00	-1.17	10	10	11	10	10	10	7	6	8	9	10	9
Valladolid	AEMET	41.65	-4.77	5	5	4	5	5	3	4	3	4	2	2	5
Sevilla	GTER	37.40	-6.05	6	7	8	6	5	3	5	4	5	3	4	5

Table 1 Stations and number of valid months used in the development of the model.

Measurements recorded in other 16 meteorological stations also belonging to the AEMET, have been used to evaluate the accuracy of the resulting expressions. In this case, the period of time employed and the data validation process is similar to that applied in the previous stations. The following table shows the geographical coordinates and the number of valid months for every station:

Station	BdD	Latitude	Longitude	Valid months											
				Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec
Albacete	AEMET	43,37	-8,42	1	1	2	2	2	2	1	1	1	0	1	1
Badajoz	AEMET	40,45	-3,72	2	3	3	3	4	4	2	2	3	2	3	3
Barcelona	AEMET	38,00	-1,17	0	0	0	1	1	0	2	1	0	0	0	0
Cáceres	AEMET	41,65	-4,77	4	0	4	0	4	0	4	0	4	0	4	0
Córdoba	AEMET	37,40	-6,05	0	1	2	1	2	1	0	2	2	0	0	0
Lleida	AEMET	41,37	0,38	1	3	2	1	2	3	1	1	1	0	1	1
Málaga	AEMET	36,72	-4,48	2	3	2	3	2	2	1	1	0	1	1	2
Oviedo	AEMET	43,22	-5,50	8	9	7	9	7	8	6	7	7	8	9	8
León	AEMET	42,58	-5,65	1	3	3	3	2	1	1	2	3	2	3	2
Soria	AEMET	41,46	-2,28	3	2	2	3	3	3	1	2	3	2	3	3
San Sebastián	AEMET	43,30	-2,03	4	3	3	4	5	4	4	2	2	2	2	2
Salamanca	AEMET	40,95	-5,67	2	2	3	3	2	2	2	2	1	1	3	2
Santander	AEMET	43,48	-3,80	7	4	4	4	4	5	4	4	3	3	6	6
Tortosa	AEMET	40,49	0,31	3	2	2	3	3	2	1	3	2	1	4	4
Valencia	AEMET	39,48	-0,47	2	2	2	3	3	2	2	2	0	2	3	2
Zaragoza	AEMET	41,67	-1,07	10	9	8	9	9	8	8	10	10	9	8	8

Table 2 Stations and valid number of months what are used in the evaluation of the model.

2. Analysis

The purpose of this work is to develop a correlation between monthly average beam irradiance and monthly clearness index which will be used to predict monthly direct normal solar radiation values from monthly horizontal global solar radiation data.

2.1. Methodology

For every measured month in each station, the monthly extraterrestrial solar radiation has been calculated to obtain the different monthly clearness index defined as

$$K_t = \frac{H_{g0}}{H_0}$$

Where H_{g0} is the monthly horizontal global solar radiation and H_0 is the monthly extraterrestrial solar radiation.

On the other hand, the number of hours between sunrise and sunset, dh has been calculated for every month to calculate the corresponding monthly average beam irradiance I :

$$I = \frac{H_{bn}}{dh}$$

Where H_{bn} is the monthly normal direct solar radiation.

Once these parameters have been calculated for the months of the five selected stations, a least squares fit of both variables yields the expression:

$$I_{DNI}^{month} = 1,29 k_t^{month} - 0,31$$

2.2 Results

The dataset used for the fitting and the resulting model are represented in the figure 1.

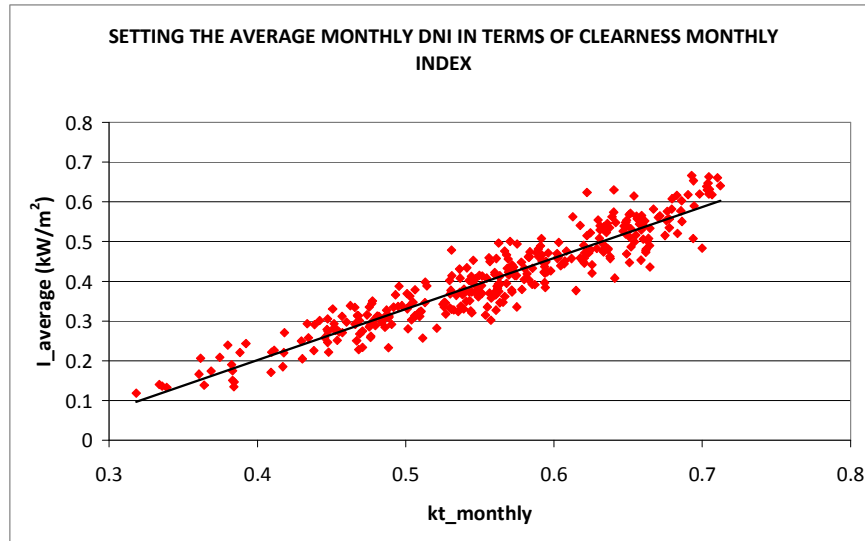


Fig. 1. Dispersion plots between monthly average beam irradiance and monthly clearness index.

It can be observed a good fitting of the data with a Mean Bias Error (MBE) of 2.75 kWh/m² and a Root Mean Squared Error (RMSE) of 15.68 kWh/m². Considering the average monthly value of the normal direct radiation from all the stations (154 kWh/m²) as a reference, the MBE represents a 1.8% and the RMSE a 10.1% of that value. These results show a good behavior of the model for these stations taking into account that it covers different latitudes and the complex performance of the atmosphere in different months of the year.

In order to evaluate the accuracy of the model with measures not used for the adjustment of the model development, we have compared the calculated monthly beam irradiation with monthly beam irradiation measured at 16 stations belonging to AEMET that were not used to adjust the model distributed throughout Spain. The results are shown in the following figure:

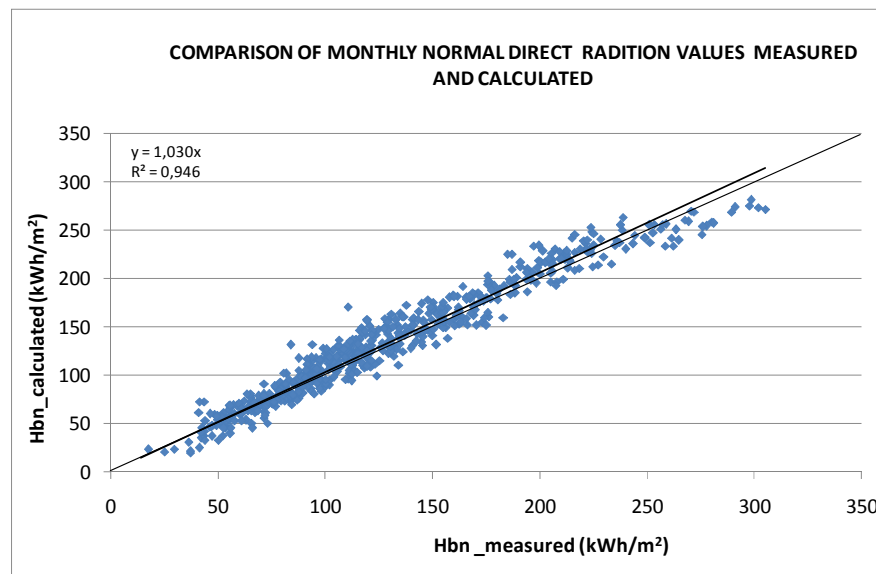


Fig. 2. Monthly normal direct radiation measured and monthly normal direct radiation calculated from the 16 selected stations from AEMET.

The figure 2 shows an average ratio of 3 % between estimate monthly direct normal radiation values from monthly horizontal global measures with a MBE of 5,3 kWh/m² and a RMSE de 14.4 kWh/m². These values are similar to those obtained with the original data used for the adjustment. In both cases, the results are quite acceptable comparing with the uncertainty introduced for the measuring devices of the normal direct irradiation around 3% for daily values.

In the figure 2 also is shown that values up to 240 kWh/m² are always sub estimated. This point will be discussed with more detailing the next section.

3.4.2. Analysis of results

Figure 3 shows the MBE and RMSE obtained when applying the model to the control set of stations, excluding Barcelona and Córdoba stations because of not having any valid months in winter.

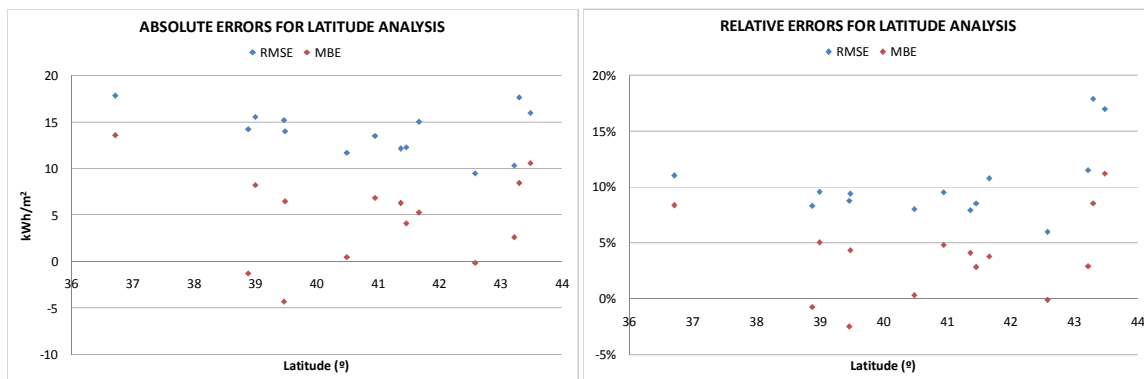


Fig. 3. Absolute and relative error obtained with every station as a function of the latitude.

In most stations, the relative¹ RMSE obtained is around 10 %, being slightly lower in the stations sited in intermediate latitudes. Only, San Sebastian and Santander reach values close to 17% exceeding clearly the mean RMSE value. Both stations are located on the North coast of Spain.

As for the relative MBE, it can be noted that in the most cases the MBE are below 5% and positive, what means that the estimated values are higher than those measured. As it with the relative RMSE, San Sebastian and Santander stations reach the highest values, around 8%, but accompanied in this case by the Malaga station, also located on the coast although with the lowest latitude of all stations.

In general, the results show that the use of a single expression, independent of the latitude, to estimate monthly direct normal irradiation values, provides a good result, although the errors may increase depending on the climatic characteristics of the area.

The monthly MBE and RMSE are shown in figure 4. The graph shows the relative RMSE values are around 10% for most of the months, the highest errors corresponding to May and December. In the case of the relative MBE, they reach their highest values on the months with highest meteorological variability (April and May).

¹ The reference value used to calculate the relative errors is the corresponding monthly average direct normal radiation value in each case.

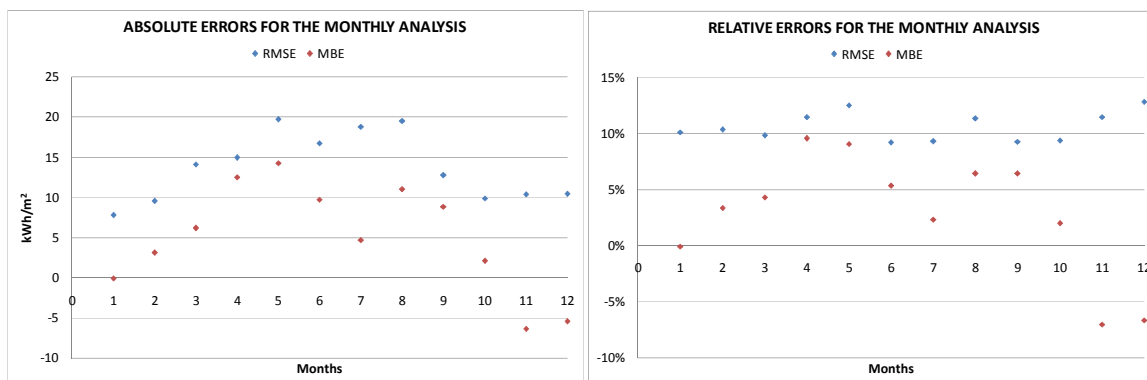


Fig. 4. Absolute and relative error obtained with every station as a function of the months of the year.

Taking into account that the meteorological variability of every month is usually different depending on the latitude, the analysis of the results as a function of both variables seems convenient. For this purpose, the absolute and relative MBE and RMSE from every month of every station are presented in tables 3 to 6. The monthly average values for all control stations are presented in table 7.

Table.3. Absolute Mean Bias Error obtained from every month of every station

MBE (kWh/m ²)	Latitud	Longitud	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec
Málaga	36,72	-4,48	9,1	12,6	19,6	3,3	15,0	25,8	29,3	38,0	X	13,3	-8,9	6,4
Badajoz	38,88	-7,02	-2,1	3,8	8,3	5,7	12,5	-3,4	-24,5	-16,6	12,4	-9,2	-11,4	-10,4
Albacete	39,00	-1,52	1,5	-6,4	-4,9	12,2	21,6	11,1	4,5	13,1	28,4	X	6,0	-8,3
Cáceres	39,47	-6,33	-4,3	-2,5	7,3	11,1	5,7	-12,6	-24,2	-11,1	2,3	-7,5	-9,6	-4,8
Valencia	39,48	-0,47	-0,7	3,0	7,4	15,2	25,4	15,4	0,6	11,1	X	3,9	-9,6	-6,4
Tortosa	40,49	0,31	-10,4	-9,0	-1,0	7,8	7,2	8,0	16,3	9,5	5,0	7,4	-8,4	-19,4
Salamanca	40,95	-5,67	8,7	13,8	8,4	15,4	10,4	13,4	-7,3	-5,2	8,9	7,9	3,2	4,3
Lleida	41,37	0,38	2,8	7,2	-4,7	16,4	7,1	17,4	-7,2	13,7	10,5	X	-5,1	-2,7
Soria	41,46	-2,28	-1,4	-3,1	-1,1	16,3	13,1	16,0	-2,2	10,9	8,1	1,4	-8,4	-7,3
Zaragoza	41,67	-1,07	-5,5	0,5	-5,0	16,7	14,5	14,2	25,4	16,7	11,1	6,9	-5,5	-5,1
León	42,58	-5,65	-0,1	-3,9	-0,4	11,4	11,4	11,3	-0,9	2,3	-1,9	-3,0	-7,7	-14,0
Oviedo	43,22	-5,50	-1,6	-0,7	5,6	10,3	1,1	2,3	9,8	14,6	6,8	2,0	-5,8	-8,5
San Sebastián	43,30	-2,03	-6,4	2,8	21,7	10,3	18,4	18,5	16,3	14,2	6,6	3,2	-9,2	-18,5
Santander	43,48	-3,80	1,6	6,9	8,9	16,4	27,1	18,6	20,6	21,0	9,2	4,3	-7,7	-1,6

Table.4. Relative Mean Bias Error obtained from every month of every station

MBE (%)	Latitud	Longitud	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec
Málaga	36,72	-4,48	8%	12%	12%	2%	7%	11%	13%	20%	X	10%	-6%	6%
Badajoz	38,88	-7,02	-3%	3%	5%	3%	7%	-1%	-8%	-6%	7%	-6%	-8%	-11%
Albacete	39,00	-1,52	3%	-5%	-3%	7%	12%	5%	2%	6%	24%	X	6%	-9%
Cáceres	39,47	-6,33	-4%	-2%	4%	7%	3%	-5%	-8%	-5%	1%	-4%	-9%	-5%
Valencia	39,48	-0,47	-1%	3%	5%	10%	15%	8%	0%	5%	X	3%	-9%	-9%
Tortosa	40,49	0,31	-9%	-9%	-1%	6%	5%	4%	7%	5%	4%	6%	-7%	-19%
Salamanca	40,95	-5,67	12%	16%	5%	11%	6%	6%	-3%	-2%	5%	7%	4%	6%
Lleida	41,37	0,38	5%	7%	-3%	15%	4%	8%	-3%	7%	7%	X	-6%	-5%
Soria	41,46	-2,28	-1%	-3%	-1%	13%	8%	8%	-1%	5%	5%	1%	-8%	-7%
Zaragoza	41,67	-1,07	-5%	0%	-3%	12%	8%	7%	13%	10%	8%	6%	-5%	-5%
León	42,58	-5,65	0%	-3%	0%	7%	6%	5%	0%	1%	-1%	-2%	-7%	-13%
Oviedo	43,22	-5,50	-2%	-1%	5%	10%	1%	2%	8%	17%	6%	3%	-9%	-12%
San Sebastián	43,30	-2,03	-13%	3%	17%	12%	18%	14%	12%	12%	6%	3%	-17%	-34%
Santander	43,48	-3,80	3%	11%	9%	15%	23%	14%	16%	18%	8%	5%	-15%	-3%

Table.5. Absolute Root Mean Squared Error obtained from every month of every station

RMSE (kWh/m ²)	Latitud	Longitud	Jan	Feb	Mar	April	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec
Málaga	36,72	-4,48	9,4	14,0	20,1	9,3	16,3	25,8	29,3	38,0	X	13,3	8,9	7,9
Badajoz	38,88	-7,02	2,8	8,5	17,6	9,9	18,0	13,5	24,8	16,8	12,5	11,3	13,6	10,4
Albacete	39,00	-1,52	1,5	6,4	10,4	14,3	22,6	17,2	4,5	13,1	28,4	X	6,0	8,3
Cáceres	39,47	-6,33	7,4	5,9	10,6	11,7	17,1	17,2	25,1	22,4	8,5	18,6	15,3	7,7
Valencia	39,48	-0,47	3,2	3,6	9,3	17,0	27,8	15,5	1,8	12,2	X	5,4	12,3	10,1
Tortosa	40,49	0,31	10,4	9,5	5,6	10,5	8,8	8,7	20,8	12,1	5,0	7,4	9,0	20,0
Salamanca	40,95	-5,67	10,4	17,4	16,9	18,5	18,5	14,1	18,2	9,8	9,6	11,4	6,5	6,0
Lleida	41,37	0,38	2,8	7,5	7,6	16,4	9,0	21,6	7,2	13,7	10,5	X	5,1	2,7
Soria	41,46	-2,28	11,8	4,1	10,4	17,0	14,7	16,6	2,2	16,0	8,9	10,5	11,2	7,3
Zaragoza	41,67	-1,07	6,6	6,6	5,3	18,0	15,1	19,3	25,4	26,3	15,4	6,9	8,8	11,8
León	42,58	-5,65	0,1	5,0	9,7	12,5	13,5	11,3	0,9	7,9	5,3	4,8	11,0	14,0
Oviedo	43,22	-5,50	5,5	4,7	7,5	12,5	7,4	10,5	12,9	17,3	9,5	9,8	7,2	13,3
San Sebastián	43,30	-2,03	9,0	9,9	34,8	12,2	20,4	19,6	18,9	14,5	9,5	5,3	12,5	18,6
Santander	43,48	-3,80	7,1	10,8	11,0	17,9	29,1	19,6	21,4	21,3	11,8	6,8	10,3	3,8

Table.6. Relative Root Mean Squared Error obtained from every month of every station

RMSE (%)	Latitud	Longitud	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec
Málaga	36,72	-4,48	8%	13%	12%	5%	7%	11%	13%	20%	X	10%	6%	7%
Badajoz	38,88	-7,02	3%	8%	11%	6%	10%	6%	8%	7%	7%	8%	10%	11%
Albacete	39,00	-1,52	3%	5%	6%	8%	13%	8%	2%	6%	24%	X	6%	9%
Cáceres	39,47	-6,33	7%	5%	6%	7%	9%	7%	9%	9%	5%	11%	14%	8%
Valencia	39,48	-0,47	4%	3%	6%	11%	17%	8%	1%	6%	X	4%	11%	14%
Tortosa	40,49	0,31	9%	10%	4%	8%	6%	5%	9%	6%	4%	6%	7%	19%
Salamanca	40,95	-5,67	14%	20%	11%	13%	10%	7%	7%	4%	6%	11%	8%	8%
Lleida	41,37	0,38	5%	7%	4%	15%	4%	10%	3%	7%	7%	X	6%	5%
Soria	41,46	-2,28	12%	4%	6%	14%	9%	9%	1%	8%	5%	8%	11%	7%
Zaragoza	41,67	-1,07	6%	6%	3%	13%	9%	9%	13%	15%	12%	6%	8%	12%
León	42,58	-5,65	0%	4%	5%	8%	7%	5%	0%	3%	3%	4%	11%	13%
Oviedo	43,22	-5,50	7%	6%	7%	12%	7%	10%	11%	20%	9%	14%	12%	18%
San Sebastián	43,30	-2,03	18%	12%	27%	14%	19%	14%	14%	12%	8%	6%	22%	35%
Santander	43,48	-3,80	13%	18%	11%	17%	24%	15%	16%	18%	10%	8%	20%	7%

Table.7. Monthly average normal direct radiation measurements

Hbn (kWh/m ²)	Latitud	Longitud	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec
Málaga	36,72	-4,48	121	107	170	171	225	227	224	187	X	130	150	115
Badajoz	38,88	-7,02	83	112	163	166	189	238	296	256	173	145	141	96
Albacete	39,00	-1,52	56	118	171	178	175	210	251	228	121	X	110	90
Cáceres	39,47	-6,33	100	124	168	159	200	250	290	247	164	176	112	102
Valencia	39,48	-0,47	81	106	157	150	165	203	255	218	X	131	110	73
Tortosa	40,49	0,31	111	97	160	130	147	192	226	196	117	126	126	104
Salamanca	40,95	-5,67	72	87	155	147	180	215	271	235	168	108	80	72
Lleida	41,37	0,38	58	101	172	107	202	212	268	206	146	X	82	52
Soria	41,46	-2,28	102	97	171	125	155	193	259	211	164	136	105	100
Zaragoza	41,67	-1,07	118	109	167	143	172	203	191	175	132	120	113	95
León	42,58	-5,65	74	117	179	160	205	216	271	229	180	124	104	104
Oviedo	43,22	-5,50	74	78	103	101	108	111	118	87	107	70	63	73
San Sebastián	43,30	-2,03	49	83	129	86	105	135	136	120	118	92	55	54
Santander	43,48	-3,80	53	62	101	107	119	130	133	118	119	84	53	54

It can be highlighted (tables 4 and 6) that the stations sited in the extreme latitudes have the worst behavior in most months, reaching the highest relative values² of MBE and RMSE. For these stations, the obtained monthly direct normal radiation values are overestimated in summer months and, especially in the North, underestimated in winter months. Also it can be stressed that, for monthly normal direct radiation measurements greater than 240 kWh/m², the calculated values are always underestimated.

² The references of the relative errors are the averages monthly normal direct radiation value shown in the table 7.

Therefore, it can be stated that the model gives worse results for places in extreme latitudes (within the range considered) or places with an special climate characteristics (close to the sea) and also that the significance of the results depends on the number of valid months used for each station.

Otherwise, the Table 4 and 5 show that the MBE from every months of every stations are higher, in most stations, than the values from every station in the figure 4.

3.4.2. Comparison with Rabl's model

The results obtained with this model (GTER model) are compared with those estimated with a similar expression developed by the Ari Rabl [1] in 1981 using 26 SOLMET stations located in the United States. In his work, Rabl found a relation between yearly average beam irradiance and yearly average clearness index, but in this case, it will be used like a relation between monthly average beam irradiance and monthly average clearness index whose physical meaning is similar. The relation found by Rabl is:

$$I_{DNI}^{month} = 1,37 \bar{k}_t^{month} - 0,34$$

To evaluated the fitting of both expressions (GTER, Rabl) in places sited throughout Spain are used the monthly measured values from all the stations used in this work. The results of the comparison are shown in the next figure:

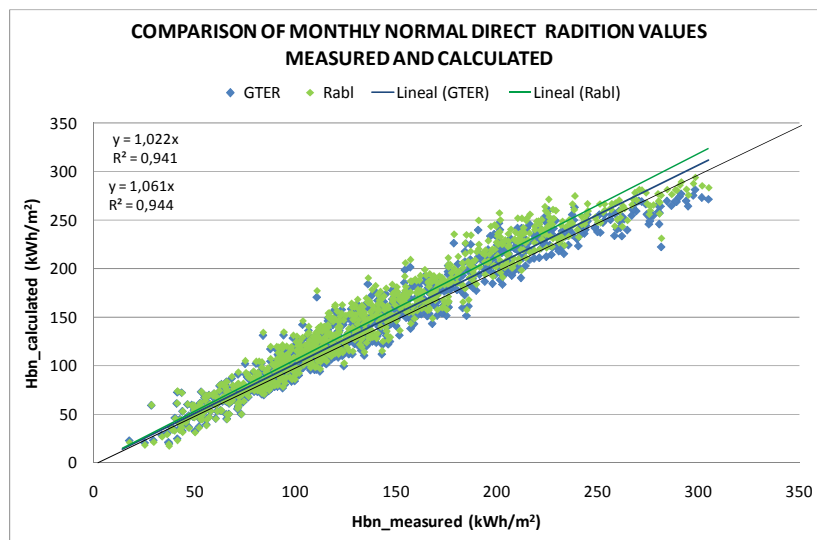


Fig. 2. Monthly normal direct radiation measured and monthly normal direct radiation calculated from the sixteen selected station from AEMET.

The clouds of points obtained with both expressions are very similar. However, the Rabl's expression provides in general higher values than those estimated with the GTER's model. The GTER's expression provide more accurate monthly direct normal radiation values from monthly horizontal global radiation measurements with a MBE about 3,2%, compared to 6,7% obtained with Rabl's expression, while the RMSE are, respectively, 10,8% and 12,8%.

Table.5. Absolute and relative Mean Bias Error and Root Mean Squared Error obtained with Rabl's and GTER's expressions

	MBE		RMSE	
	Absolute (kWh/m ²)	Relative (%)	Absolute (kWh/m ²)	Relative (%)
GTER	4,4	3,2%	14,9	10,8%
Rabl	9,2	6,7%	17,6	12,8%

3. Conclusions

In this work, it has been developed a model to estimate yearly and monthly average beam irradiance from the yearly and monthly clearness indexes. This expression has been tested with the measurements from 16 stations sited throughout Spain obtaining estimates with a MBE of 5,3 kWh/m² and a RMSE of 14.4 kWh/m². In relative terms, these errors are of the same order of magnitude of the accuracy of the sensors commonly used to measure DNI.

In a more detailed analysis, it has been found that the stations sited in the extreme latitudes have the worst behavior in the most months, reaching the highest relative values of MBE and RMSE. Another interesting result is that for monthly normal direct radiation measurements greater than 240 kWh/m², the calculated values are always underestimated. The model gives worse results for places sited in extreme latitudes within the range of this analysis or places with especial climatic characteristics. These results suggest the need to develop a different specified expression for certain sites.

The errors resulting when applying the model (a single expression) to the estimation of monthly DNI values are somewhat higher relative RMSE around 10 % and relative MBE below 5% for most stations, except those located in extreme latitudes. In general, the results show that the use of a single expression, independent of the latitude, for estimating monthly DNI values, provides an acceptable result, considering that the errors may increase depending on the climatic characteristics of the area.

Finally, the results obtained with the GTER's model have been compared with those estimated with a similar expression developed by Rabl. GTER's expression provides more accurate yearly and monthly DNI estimates from monthly horizontal global radiation measurements with a MBE about 3,2%, compared to 6.7% obtained with Rabl's expression. However, the errors are comparable despite the fact that Rabl's model was developed with data from a different region, what makes this type of expressions very useful for a first estimate of DNI from global irradiation values when no local models are available.

References

- [1] A. Rabl, Yearly average performance of the principal solar collector types, *Solar Energy* 27, 215-233 (1981).