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DNI Measurements in the South of Portugal: Long Term Results through Direct Comparison with Global and Diffuse Radiation Measurements and Existing Time Series

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Abstract. The present work describes the measurement effort for direct normal irradiance (DNI) evaluation in the sunny south of Portugal, with a network of eight radiation measurement stations in several locations (including Évora) providing a good coverage of the region. This new initiative for DNI measurement will still need many years (typically 10 or more) to produce a time series which can claim having long term statistical value. This problem can, however, be temporarily mitigated by measuring DNI at the same time as GHI and DHI, in a place where long term series dating back, already exist for those two. It so happens that a long term series (20 years) of global and diffuse solar irradiation exists for the location Évora. So the expectation is to establish correlations with the goal of attributing at least some long term statistical significance to the short and recent DNI series. The paper describes the setup of the measuring stations and presents the preliminary measurements obtained. It further presents the first correlations of monthly averages between normal beam (DNI), global and diffuse radiation. It then uses these correlations, admittedly without acceptable statistical significance (short series of less than one year of measured data), to exemplify how to get a prediction of long term DNI for Évora. This preliminary obtained value is compared to that predicted by the commercial data from Meteonorm.

$I_{b,n}$	Instantaneous beam irradiance at normal incidence
I_h	Instantaneous hemispherical irradiance
I_d	Instantaneous diffuse irradiance
$\overline{I}_{b,n}$	Hourly monthly average beam irradiance at normal incidence
$\overline{I}_h$	Hourly monthly average hemispherical irradiance
$\overline{I}_d$	Hourly monthly average diffuse irradiance
$\overline{H}_{b,n}$	Daily Monthly average beam irradiation
$\overline{H}_h$	Daily Monthly average hemispherical irradiation
$\overline{H}_d$	Daily Monthly average diffuse irradiation
Θ	Solar zenithal angle

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INTRODUCTION

Solar Energy concentration can be used in different applications, including industrial process heat, desalination or solar electricity production among others. The use of solar concentrators requires the knowledge of direct normal irradiance (DNI) however this data is generally not available on a large scale. In particular, it is very important to know the long term availability of DNI at any given location where the installation of a solar concentrating system is planned for. Global (GHI) and diffuse horizontal irradiance (DHI) measurements have been made all over the world in the last decades and a good geographical cover exists, even with long term series in many locations. These measurements are simple to make with fixed detectors, just requiring small tilt adjustments on the shadow band (every few days) in the case of DHI, plus very simple maintenance operations. That is not the case with DNI, requiring accurate continuous tracking of the sun's apparent motion. In the last few years applications like STE (Solar Thermal Energy) and CPV (Concentrating Photovoltaics) are strongly driving the need for setting up DNI measuring stations and the collection of reliable long term ground based data, enabling the proper sizing of solar systems and enough confidence on the results to facilitate financing and insuring the heavy investments associated with these systems.

This kind of investments is best done with reliance on accurate solar resource measurements, always preferable to modeled data and their associated uncertainties. But setting up DNI measurement stations to cover a significant area and time span is costly and takes time. Therefore the need exists for the development of DNI models based on reliable ground measurements and with predictions as reliable as possible. In the past, several comparisons have been made between existing datasets and different models, showing significant disagreement in DNI predictions for different locations [1]. This in spite of a large variety of models to infer DNI from atmospheric data or from GHI data. In general, models have difficulty with giving good results for locations other than the one they were derived for [1] [2] [3].

However a new initiative for DNI measurement will need many years (typically 10 or more) to produce a time series that can be claimed to have a long term statistical value. So there is hope that this problem can perhaps be partially resolved by measuring DNI at the same time as GHI and DHI, in a location where long term series dating back a few years, already exist for those last two. Correlations [4] will then be established to help attribute a long term statistical value to short and recent DNI series. It so happens that in this same location past long term series of atmospheric data also exists [5].

The present work describes the measurement effort just launched by the authors in the sunny south of Portugal, with a network of radiation measurement stations in several locations (including Évora), providing good coverage of the region and the use of long term series (20 years) of global and diffuse solar irradiation measured in Évora [5] [6]. An identical station is installed in Oporto, in a less sunny north of Portugal, to be used as a contrast point. This paper has the goal of establishing a series of measuring stations over a large area (the South of Portugal) to collect good quality data and make it available to all users. It also has the long term goal of contributing to the quality assessment of DNI models.

NETWORK OF STATIONS IN THE PROGRAM: INSTALLATION, CALIBRATION AND MAINTENANCE

The participating sites are evenly distributed in the center and south of Portugal. There is a participating station in the north of Portugal (Oporto - INEGI), a location known for a lower average value of DNI and, as such, not so interesting for STE or CPV applications. This contrast should be apparent in the final results and should help the production of a clearer picture of the country's DNI potential. The locations chosen are: two on the western Atlantic coast (Lisbon – LNEG; and Sines – University of Évora), Évora, sort of in the center and all the others (Portalegre – AREANATejo; Moura – Lógica; and Martim Longo – Capwatt) closer to and along the portuguese-spanish border, should provide good conditions for the coverage of different and relevant average conditions and a reliable geographical extrapolation for any location in the whole region. Figure 1 (a), below, shows the locations chosen for the network of DNI, global and diffuse measuring stations and a view of one of the stations (Mitra).

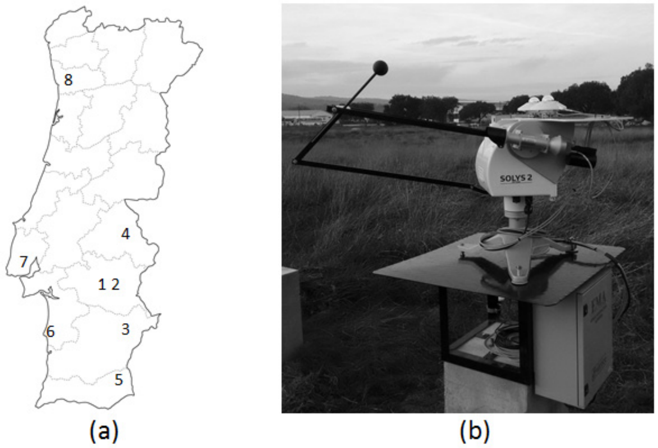

FIGURE 1. (a) DNI, GHI and DHI measuring stations network, and (b) view of one of the stations (Mitra).

All stations have been installed and some have already been providing data since the end of 2014, the last one started measuring only in April 2015. As an example, the Mitra station (in the vicinity of Évora city) shown in Figure 1 (b) consists of a sun tracker, model Solys2 [7] with a shading ball assembly [7] for diffuse radiation measurement, one pyrheliometer model CHP 1 [7], two pyranometers model CMP 11 [7] and a data logger (DT80) [8] for data acquisition, data storage (buffer) and communication. The same instruments are used in all other stations. A process of relative calibration is under way. The procedure is to take the same reference pyrheliometer and pyranometer around, to every station, and compare readings, making sure that all instruments are measuring with relative consistency, following the ISO Standards 9059:1990 and 9847:1992. Besides, another permanent degree of measurement consistency is obtained through the comparison of the measurements obtained for GHI (I_h), DHI (I_d) and DNI ($I_{b,n}$) with Equation (1) [9]:

$$I_h = I_{b,n} \times \cos(\theta) + I_d \quad (W/m^2) \tag{1}$$

where Θ is the instantaneous solar zenithal angle, which is the same angle as between beam radiation and the sensing element for the pyranometer measuring hemispherical irradiance.

This consistency is a way of fully using the fact that three high quality instruments are measuring the same solar input, with the pyrheliometer and its tracking system aligned with the apparent solar position, adding significant confidence and accuracy to the final result. All the radiometers were also checked for their zero offset. This correction was carried out by finding the average of two other mean values: the signal output during the 60 minute interval before the morning astronomical twilight (Θ>108°) for the same day and the equivalent period after the sunset. This mean zero offset is then subtracted to the measured data. This method of zero offset correction is a standard procedure and assumes that the instruments net exchange of infrared radiation with the environment remains constant throughout the solar day [10].

A cleaning protocol for the instruments was defined and implemented. The instrument domes and desiccant check were done once a week. In the near future there will conditions to increase this periodicity in every network station.

MEASUREMENTS AND FIRST RESULTS

The DNI, GHI and DHI measurements are made on a 5-second time step and recorded for each minute. In this work hourly and monthly values are used. Tables 1, 2 and 3 show the first measurements of $\overline{H}_{b,n}$, $\overline{H}_h$ and $\overline{H}_d$ (corresponding to the average daily monthly beam, hemispherical and diffuse irradiation in kWh/m^{2}day) for each station, based on 1-min average values. The data shown for each location does not cover exactly the same period of time, since the project started recently with various installations in different locations, which also resulted in different startup dates. There are also some data gaps due to different reasons, such as technical issues, maintenance and calibration activities. The station in Martim Longo is not measuring diffuse radiation. However another and fully equipped station is expected to be installed very soon near the existing one and also integrated into the network.

TABLE 1. $\overline{H}_{b,n}$ (kWh/m^2/day) measured for each station since the beginning of the project.

	1-Évora	2-Mitra (Évora)	3-Moura	4-Portalegre	5-Martim Longo	6-Sines	7-Lisboa	8-Porto
June 14	Not installed	Not installed	7,4	7,0	5,1	Not installed	7,1	(a)
July 14			(a)	8,2	8,7		8,1	
Aug. 14				(a)	8,5		(a)	
Sept. 14			4,5		4,6		4,1	
Oct. 14			4,2		4,0		2,9	
Nov. 14			2,4		2,2		1,6	
Dec. 14			3,6		4,1		4,1	
Jan. 15		4,2	4,3		4,5		3,9	
Feb. 15		4,4	4,5		4,3		3,6	
Mar. 15	6,2	6,0	6,2		5,6		5,8	4,7
April 15	4,2	3,7	4,4	4,2	4,2		4,2	4,2
May 15	8,1	7,4	(a)	7,6	7,7	7,8	7,9	7,0
June 15	7,9	6,9	7,8	6,8	7,7	6,7	7,6	6,8

(a) Unavailable data

TABLE 2. $\overline{H}_h$ (kWh/m^2/day) measured for each station since the beginning of the project.

	1-Évora	2-Mitra (Évora)	3-Moura	4-Portalegre	5-Martim Longo	6-Sines	7-Lisboa	8-Porto
June 14	7,4	Not installed	7,6	7,1	5,3	Not installed	7,1	(a)
July 14	7,6		(a)	7,5	7,8		7,5	
Aug. 14	7,5			(a)	7,3		(a)	
Sept. 14	4,7		4,8		4,9		4,4	
Oct. 14	3,6		3,7		3,7		3,2	
Nov. 14	2,1		2,4		2,3		1,8	
Dec. 14	2,4		2,2		2,4		2,2	
Jan. 15	2,6	2,5	2,6		2,7		2,3	
Feb. 15	3,1	3,3	3,4	3,2	3,6		3,0	
Mar. 15	5,1	4,8	4,9	4,1	4,9		4,8	5,1
April 15	4,7	5,2	5,2	5,0	5,3		4,8	4,9
May 15	7,4	7,2	(a)	7,2	7,4	7,5	7,3	6,8
June 15	7,4	7,1	7,7	7,1	7,5	7,0	7,3	7,2

(a) Unavailable data

TABLE 3. $\overline{\mathrm{H}}_\mathrm{d}$ (kWh/m^2/day) measured for each station since the beginning of the project.

	1-Évora	2-Mitra (Évora)	3-Moura	4-Portalegre	5-Martim Longo	6-Sines	7-Lisboa	8-Porto
June 14	2,5	Not installed	2,3	2,1	No DHI measurements	Not installed	1,5	(a)
July 14	1,8		(a)	1,6			1,4	
Aug. 14	1,7			(a)			(a)	
Sept. 14	1,9		1,9				1,6	
Oct. 14	1,4		1,5				1,4	
Nov. 14	1,2		1,3				1,0	
Dec. 14	0,8		0,8				0,6	
Jan. 15	0,8	0,8	0,9				0,7	
Feb. 15	1,1	1,2	1,2	1,2			1,1	
Mar. 15	1,4	1,4	1,4	1,3			1,2	2,0
April 15	2,2	2,6	2,2	2,2			1,8	2,1
May 15	2,3	1,9	(a)	1,6		1,8	1,5	2,0
June 15	2,3	2,2	2,0	1,8		2,0	1,5	2,2

(a) Unavailable data

As a validation procedure, Equation (1) can be rewritten to yield Equation (2):

$$\cos(\theta) = \frac{(I_h - I_d)}{I_{b,n}} \tag{2}$$

Therefore, Figure 2 can be obtained by plotting the cosine of zenith resulting from the ratio shown in Equation (2), but now calculated as a function of the average hourly values, against the cosine of the average hourly angle.

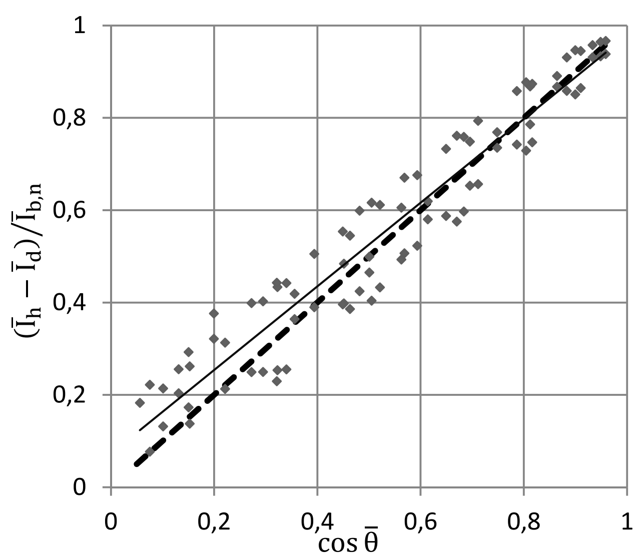

FIGURE 2. Comparison of the cosine of zenith calculated through the measurements, Equation (2), with the cosine of the average zenith angle for each hour.

A least square fit of plotted values can be made (solid line), with an R^2= 0.93, yielding the follow Equation:

$$\frac{\left(\bar{I}_h - \bar{I}_d\right)}{\bar{I}_{b,n}} = 0.91 \times \cos(\bar{\theta}) + 0.07 \tag{3}$$

As shown in Figure 2, this fit deviates slightly from the broken line, of slope 1; this deviation can be attributed mainly to a larger cosine effect error in radiometers for high zenithal angles (>80º) and to a random dispersion around unit slope, in general because during an hour, significant variations can be observed, especially from the change between clear and cloudy moments.

In future work these data will be analyzed and compared, once the amount of data gathered exceeds at least one full year. In the meantime, and as an example of the investigations that can be done, the data gathered at the Mitra station (and that one only) is used below.

CORRELATION FOR MONTHLY AVERAGE VALUES OF DNI IN RELATION TO GHI AND DHI MEASUREMENTS

Weather variability affects the amount of incident solar radiation in any given place. Long-term average behavior is quite important for solar energy applications, their performance estimate and guarantee.

As stated above, many stations do not measure DNI and it is interesting to be able to retrieve the DNI value from GHI and/or DHI measurements. But, quite beyond that, once just a few years of DNI data are gathered in this project, it is legitimate to ask how representative of long term behavior the measured short term series thus obtained is. This paper makes the assumption that if correlations between measured DNI, GHI and DHI are made with the measured data, these should also hold for the same location in respect to long-term series of GHI and DHI data obtained in the past, thus allowing for a more reliable "long-term" estimate of DNI. For this purpose the paper will use 10 years (later even 20 years) of data already available and processed for the city of Évora, including GHI and corrected DHI data (with shadow band correction) [12].

Firstly, the measured monthly data from the new station in Mitra (10 km from Évora) was compared to the corresponding 10 year monthly averages (see table 4) and for the first seven months of 2015. This comparison shows that the measured values are close to the 10 year average ones.

TABLE 4. Comparison between $\overline{H}_h$ and $\overline{H}_d$ measured values and 10 year series average.

		Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**
$\overline{H}_h$ (kWh/m²/day)	Mitra measurements*	2,5	3,3	4,8	5,2	7,2	7,1	7,9
	10 year series average	2,4	3,3	4,5	5,6	6,8	7,7	8,0
$\overline{H}_d$ (kWh/m²/day)	Mitra measurements*	0,8	1,2	1,4	2,6	1,9	2,2	1,5
	10 year series average	0,9	1,3	1,8	2,6	2,6	2,3	1,8

* The same values in Tables 2 and 3.

With the measured data presented above, Table 1-Monthly daily averages of DNI and the corresponding GHI and DHI of Table 4, the graphic in Figure 3 can be produced.

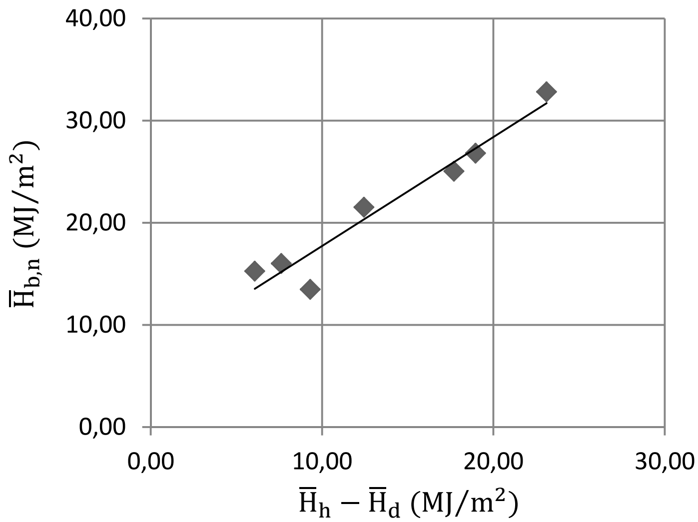

FIGURE 3. Measured $\overline{H}_{b,n}$ (MJ/m^2) as function of $\overline{H}_h$-$\overline{H}_d$ (MJ/m^2).

A preliminary linear least square fit (R^2=0.94) can be made, Equation (4):

$$\overline{H}_{b,n} = 1.07 \times \left(\overline{H}_h - \overline{H}_d\right) + 7.04 \ \ (MJ/m^2) \tag{4}$$

With more data the significance and the correlation factor will certainly be better, allowing an improved estimation of monthly average DNI values.

It is worth to note that if this correlation is assumed to have a relevant statistical value and adequately represent the whole year, it is possible, by using the average $\overline{H}_h$ and $\overline{H}_d$ of the 10 year series, to estimate the $\overline{H}_{b,n}$ value for each month and thus the total expected average DNI for this specific location. This exercise was attempted and Table 5 is the result, yielding a result for the average expected DNI of 1985 kWh/m^2/yr.

TABLE 5. $\overline{H}_h$ and $\overline{H}_d$ average values for the ten year data series and estimated $\overline{H}_{b,n}$.

	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
$\overline{H}_h$ (kWh/m^2/day)	2,4	3,3	4,5	5,6	6,8	7,7	8,0	7,0	5,5	3,7	2,5	2,1
$\overline{H}_d$ (kWh/m^2/day)	0,9	1,3	1,8	2,6	2,6	2,3	1,8	1,8	1,8	1,4	1,0	0,8
$\overline{H}_{b,n}$ (kWh/m^2/day)*	3,6	4,1	4,8	5,2	6,5	7,7	8,7	7,5	5,9	4,4	3,6	3,3

* Results from Equation (4).

This value can be compared with the long term estimates which are easily obtained from data sets produced by data generating algorithms. A possible choice is Meteonorm which yields a value of 2118 kWh/m^2/yr for the Évora location (with an uncertainty of 85 kWh/m^2/yr) [12]. The preliminary value obtained (1985kWh/m^2/yr) is lower and slightly outside the uncertainty range indicated. No big significance is attributed to this fact at this stage, given the very short amount of data (not even a complete year) used in this calculation.

CONCLUSIONS

A very preliminary report was made on a new initiative concerning the DNI measurement in the South of Portugal, where a total of seven measuring stations for beam, global and diffuse radiation were set up. An extra station in the North of the country (OPorto) was also included in the study to clearly establish the known north-south expected differences.

These stations will be operated for a few years and several types of analysis are planned to be made with the data gathered. Among them is the idea of adding long term, statistical significance to the beam radiation measured, by establishing correlations with Global and Diffuse radiation at one of the locations (Évora) with long term series of Global and Diffuse solar radiation data available for that location.

The paper reported on the first few months of data and, as an example of the method proposed, attempted a calculation of the average beam radiation to be expected on a yearly basis. The value obtained of 1985 kWh/m^2/yr is slightly below the value of 2118 kWh/m^2/yr (± 85 kWh/m^2/yr) estimated for the location by Meteonorm [12].

However it is clear that no firm conclusions should be made yet from the amount of data gathered up to now.

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REFERENCES

[1] Gueymard, C.A.: Progress in direct irradiance modeling and validation. Proc. Solar Conf., Phoenix, AZ, American Solar Energy Society (2010)
[2] R. Perez, et al.: Climatic evaluation of models that predict hourly direct irradiance: prospects for performance improvements. Solar Energy, 44 (2), 99–108 (1990)
[3] F.J. Batlles, M.A. Rubio, J. Tovar, F.J. Olmo, L. Alados-Arboledas.: Empirical modeling of hourly direct irradiance by means of hourly global irradiance. Energy 25, 675–688 (2000)
[4] Collares-Pereira, M., Rabl, A.: The average distribution of solar radiation correlations between Diffuse and hemispherical and between daily and hourly insolation values. Solar Energy 22(2), 155-164 (1979)
[5] Mateos, D., A. Sanchez-Lorenzo, M. Antón, V. E. Cachorro, J. Calbó, M. J. Costa, B. Torres, and M. Wild (2014), Quantifying the respective roles of aerosols and clouds in the strong brightening since the early 2000s over the Iberian Peninsula, J. Geophys. Res. Atmos., 119, doi:10.1002/ 2014JD022076.
[6] Salgueiro, V., Maria João Costa, Ana Maria Silva, and Daniele Bortoli, 2014: Variability of the Daily-Mean Shortwave Cloud Radiative Forcing at the Surface at a Midlatitude Site in Southwestern Europe. J. Climate, 27, 7769–7780. doi: http://dx.doi.org/10.1175/JCLI-D-13-00696.1
[7] Kipp & Zonen, retrieved from http://www.kippzonen.com/
[8] DataTaker, retrieved from http://www.datataker.com/DT80.php
[9] Rabl, A., Active Solar Collectors and Their Applications, (Oxford University Press, New York 1985)
[10] McArthur L.J.B., Baseline Surface Radiation Network (BSRN), Operations Manual, (2005)
[11] Iqbal, Muhammad, An Introduction to Solar Radiation, (Academic Press, New York, 1983), Chap. 12, 362-365
[12] Meteonorm yearly irradiation data