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# A simplified method for estimating direct normal solar irradiation from global horizontal irradiation useful for CPV applications

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ABSTRACT

The design and analysis of CPV systems require knowledge of direct normal solar irradiation but ground-based measurements of these data are only available for very few locations. Nowadays, meteorological databases that estimate direct normal irradiation from satellite images and other data sources are used. However, values provided by the different existing databases show large dispersion due to different estimation methods, input data and base years. In this paper, a simplified method for calculating direct normal irradiation is presented. It has been obtained from previous models proposed by several authors. One of its advantages is that it only requires latitude and global horizontal irradiation as input data. As global irradiation is easy to find or measure, the procedure becomes a useful tool in renewable energy applications. The accuracy of this method is similar to that of the existing databases and it is able to easily generate a mass of direct normal irradiation data for different areas worldwide.



**Contents**



## 1. Introduction

Photovoltaic devices are at a mature technological stage with a long and wide field experience, but if this energy source wants to compete against other renewable energy sources or even to get into the traditional energy generation system, further scientific progress in the behavior of these kinds of systems is necessary. Concentrator Photovoltaic (CPV) technology can have a main role in this challenge, as it has proved, in recent published research, to have the potential to achieve high levels of energy conversion performance [1].

CPV is based on the use of optical devices that increase the light received on the solar cell surface. The concentration mechanism is achieved by lenses or mirrors that either refract or reflect the incoming light from the sun on top of the cell receiver surface. Depending on the concentration process, as well as on the concentration area, there is a wide range of optical device configurations that can be used in the implementation of a CPV module [2].

The use of concentrators implies that CPV systems only work with the Direct Normal Irradiance (DNI). So it is necessary to know DNI data in order to estimate the energy that will be produced by the system, perform economic analysis, supervise plant operation, etc. However, DNI ground-based measurements

*Abbreviations:* CPV, concentrator photovoltaic; DNI, direct normal irradiance or irradiation; TMY, typical meteorological year; HC, HelioClim; HCPV, high concentration photovoltaic

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**Nomenclature**

| | |
|---|---|
| $B_0$ | solar constant (W/m$^2$) |
| $\delta_{dn}$ | solar declination of the day in the middle of each month (radians) |
| $d_n$ | day number of the year (dimensionless) |
| $\varepsilon_{o\ dm}$ | eccentricity correction factor of the earth's orbit of the day in the middle of each month (dimensionless) |
| $G_{G\ hm}(0)$ | monthly average hourly global irradiance on a horizontal surface (W/m$^2$) |
| $G_{B\ hm}(0)$ | monthly average hourly direct irradiance on a horizontal surface (W/m$^2$) |
| $G_{D\ hm}(0)$ | monthly average hourly diffuse irradiance on a horizontal surface (W/m$^2$) |
| $G_{B\ hm}(S)$ | monthly average hourly direct normal irradiance (W/m$^2$) |
| $H_{G\ dm}(0)$ | monthly average daily global irradiation on a horizontal surface (Wh/m$^2$) |
| $H_{BO\ dm}(0)$ | monthly average daily extraterrestrial irradiation on a horizontal surface (Wh/m$^2$) |
| $H_{B\ dm}(0)$ | monthly average daily direct irradiation on a horizontal surface (Wh/m$^2$) |
| $H_{D\ dm}(0)$ | monthly average daily diffuse irradiation on a horizontal surface (Wh/m$^2$) |
| $H_{B\ dm}(S)$ | monthly average daily direct normal irradiation (Wh/m$^2$) |
| $H_{B\ a}(S)$ | annual direct normal irradiation (Wh/m$^2$) |
| $K_{Tm}$ | clearness index (dimensionless) |
| $K_{Dm}$ | diffuse fraction of global radiation (dimensionless) |
| $\varphi$ | latitude (°) |
| $\omega$ | solar hour angle (radians) |
| $\omega_{s\ dm}$ | Sunrise hour angle of the day in the middle of each month (radians) |

are expensive and rarely available due to the cost and sophistication of measurement devices and data processing requirements. There is a particular lack of data in the Sunbelt countries, which are more favorable for the use of CPV.

This lack of DNI data contrasts with the availability of global horizontal irradiation data, which are easy to find or measure. So it seems to be interesting to have a procedure that obtains DNI from global irradiation.

We can find in the literature several models for calculating DNI from different parameters [4–8]. These models are accurate but some of them are complex and difficult to apply, especially because they require input data that is not easy to obtain, for instance measurements taken from satellite images. In this paper, a simplified method obtained from previous models is presented. Its aim is not to improve the existing models, but to easily provide DNI only by using latitude and global horizontal irradiation as input data. The accuracy of the method seems to be acceptable for its use in CPV applications.

## 2. DNI data sources

Preferably, Typical Meteorological Year (TMY) data should be used for the analysis and design of CPV systems. These datasets are based on measurements taken from ground meteorological stations for ten years [3]. However, due to equipment costs, such measurements are scarce and TMY datasets are available for only a very few locations. An alternative solution to this problem is the use of a model that derives DNI from satellite data. In recent years, several methods for estimating direct normal irradiance and irradiation from satellite data have been proposed [4–8]. Nevertheless, the use of these procedures is often difficult as is obtaining the satellite data. Thus, spatial databases that directly provide DNI are usually utilized.

There are a number of spatial databases that provide DNI values for different places and time intervals (Meteonorm [9], NASA-SSE [10], PVGIS [11], PVSAT [12], Satel-Light [13], SoDa [14], SOLEMI [15], etc.). These databases use different kinds of input data (satellite data, ground-based measurements) and different procedures in order to estimate DNI values. They are a very useful tool for the design and evaluation of CPV systems. However, some databases show weaknesses: there is a lack of continuity in the data because the information comes from a limited number of ground stations and there are no hourly DNI data, except for a very few sites. Although the main problem is uncertainty because DNI values provided by the different databases show large dispersion. The result is a fragmentation of services, each having its own mechanism of access and all giving different outputs due to different methods, input data and base years.

In order to analyze this uncertainty, a comparison between measured DNI values taken from ground meteorological stations located at three Spanish places (Madrid, 40.417N –3.700W; Murcia, 37.983N 1.130W and Jaén, 37.766N–3.790W) and DNI values provided by three databases (SoDa, NASA-SSE and PVGIS) for these three locations has been made.

DNI measurements for Madrid have been carried out by the Solar Energy Institute (Instituto de Energía Solar, IES) in 2006, 2007 and 2010. DNI measurements for Murcia have been carried out by the Meteorology State Agency (Agencia Estatal de Meteorología, AEMET) from 2005 to 2010. And DNI measurements for Jaén have been carried out by the University of Jaén in 2001, 2002, 2003 and 2010. In every case, a pyrheliometer with wavelength range from 0.2 to 4 μm has been used for the DNI measurements.

SoDa website disseminates the HelioClim (HC) databases which contain radiation values at ground level obtained from the processing of the images taken by Meteosat satellites. In this case, the HC databases are processed by MINES ParisTech. On the other hand, NASA-SSE release 6 combines results from GEWEX/SRB 3 and ISCCP projects with NCAR reanalysis products (1983–2005). The database directly provides monthly and annual DNI values around the world. Finally, PVGIS includes solar radiation developed by a combination of solar radiation models and interpolated ground observations, representing the period 1981–1990. It does not directly provide DNI but this can be estimated from global and diffuse radiation components.

Table 1 compares measured values taken from the meteorological stations to values provided by the databases. Annual DNI value measured at Madrid is 1882 kW h/m$^2$ while the different databases give values between 1814 and 1964 kW h/m$^2$. This implies an error between −3.6% and 4.4%. Annual DNI value

**Table 1**
Annual DNI values for three Spanish locations (kW h/m$^2$).

| Location | Measured | SoDa | NASA-SSE | PVGIS |
|---|---|---|---|---|
| MADRID | 1882 | 1947 | 1964 | 1814 |
| MURCIA | 1961 | 1738 | 1905 | 1870 |
| JAÉN | 1984 | 2208 | 2132 | 1745 |