SOLAR RADIATION ESTIMATION AND PREDICTION USING MEASURED AND PREDICTED AEROSOL OPTICAL DEPTH (AOD)

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Abstract

As the world's most abundant renewable resource, solar energy is expected to play a key role in the future global energy supply. Given the fluctuating nature of solar irradiation, its efficient use requires reliable measurement and forecasting its availability on several temporal and spatial scales, depending on the application. This paper validates previously published clear sky models which accurately estimate solar irradiation data using aerosol optical depth (AOD) measurements. The validated clear sky models presented can be useful tools for confirming the goodness of both global horizontal and direct normal irradiation measurements. It also proposes a simple method for predicting irradiation by means of irradiation measurements and forecast AOD. Moreover, measured AOD is shown to be required for prediction, as estimation of DNI using satellite-derived AOD data has been found to be inaccurate.

1. Introduction

The large-scale integration of solar energy sources into current energy supply structures demands both the development of advanced technologies and the availability of precise information on the solar resource. Direct normal solar irradiation (DNI) is highly variable in space and time, and its variation exerts significant influence on electric power generation by Concentrated Solar Power (CSP) systems. Therefore, precise evaluation of DNI is required for planning CSP systems at specific locations. Given the inherent difficulty in measurement of Direct Normal Irradiation (DNI) due to solar tracking among other problems, and the uncertainty of DNI estimation derived from satellite data, it is desirable to have an alternative source of estimation to confirm the goodness of measurements, or to detect sources of error in them.

Another related key issue is the prediction of solar irradiation at different time scales, as required by the given application (ranging from sub-hourly to several days). Among these applications, we might mention storage management in stand-alone photovoltaic (PV) systems, building control systems, solar thermal power plant (STTP) control, and management of electricity grids with high renewable penetration rates (see Fig.1).

To overcome these difficulties, this paper presents two clear sky models which provide DNI from Aerosol Optical Depth (AOD, a quantitative measurement of solar irradiation extinction by aerosol scattering and absorption), which can be used to validate DNI measurements due to their simplicity and accuracy. The choice of model depends on the meteorological and AOD data available. A simple method for predicting DNI data from forecast AOD by combining DNI measurements and clear sky model predictions is also proposed.

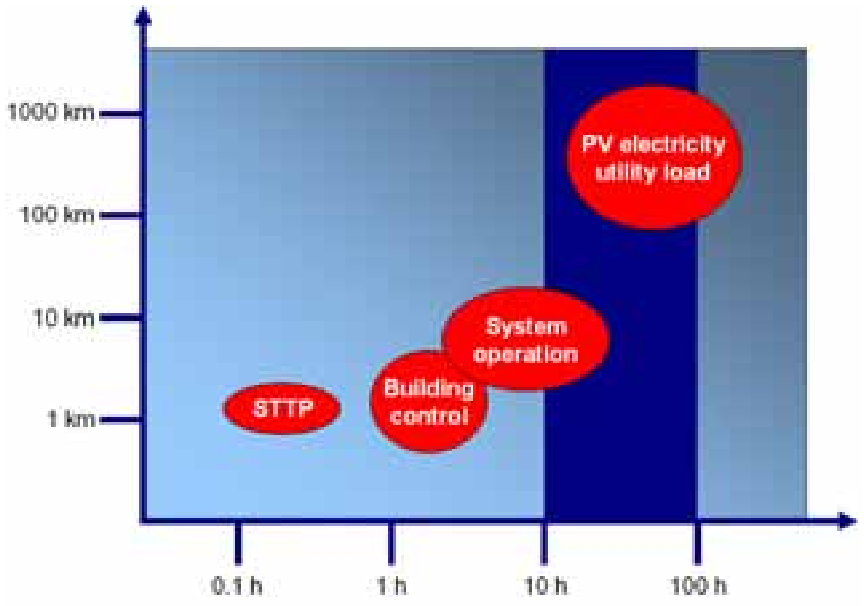

Fig. 1. Spatial and temporal solar irradiation forecasting scales and their typical target applications. The range where the method presented in this paper works best is shown in dark blue (adapted from [1]).

2. Material and methods

2.1. Solar irradiation and AOD measurements

Measured one-minute solar radiation data were downloaded from the Baseline Surface Radiation Network (BSRN, http://www.bsrn.awi.de/) station in Carpentras, France. AOD data and atmospheric water-vapour content for the same location were downloaded from the AErosol RObotic NETwork (AERONET, http://aeronet.gsfc.nasa.gov/), and from GES DISC Interactive Online Visualization ANd aNalysis Infrastructure (Giovanni, http://disc.sci.gsfc.nasa.gov/giovanni/). AOD and cloud cover forecasts were calculated using the BSC-DREAM8b model:

(http://www.bsc.es/plantillaH.php?cat_id=321).

2.2. Simplified Solis clear sky model

The clear sky model proposed in [2] was used for solar radiation estimation. This model is a simplified version of the Solis clear sky model, and was chosen due to its simplicity and accuracy compared to the Solis model itself. It is based on a modified Beer-Lambert equation, for which model parameters are calculated analytically.

2.3. Ineichen and Pérez clear sky model

[3] modifies existing direct (beam) and global irradiance clear sky models to better take into account radiation's dependence on station altitude and the solar geometry.

3. Results

3.1. DNI estimation using AOD measurements

To validate the clear sky model presented in [2], DNI measurements and estimations in the above location were compared, with satisfactory results (the annual difference is about 0.7%).

Fig. 2 (top) shows a comparison between estimated (blue line) and measured (red line) DNI at the Carpentras station under clear sky conditions. Estimation was performed using the clear sky model presented in [2], with atmospheric water vapour content and AOD measurements (at 380 and 500 nm). AOD at 700 nm (required by the model) were derived from the Bird & Hulstrom equation [4]:

$AOD_{700} = 0.27583 \cdot AOD_{380} + 0.35 \cdot AOD_{500}$

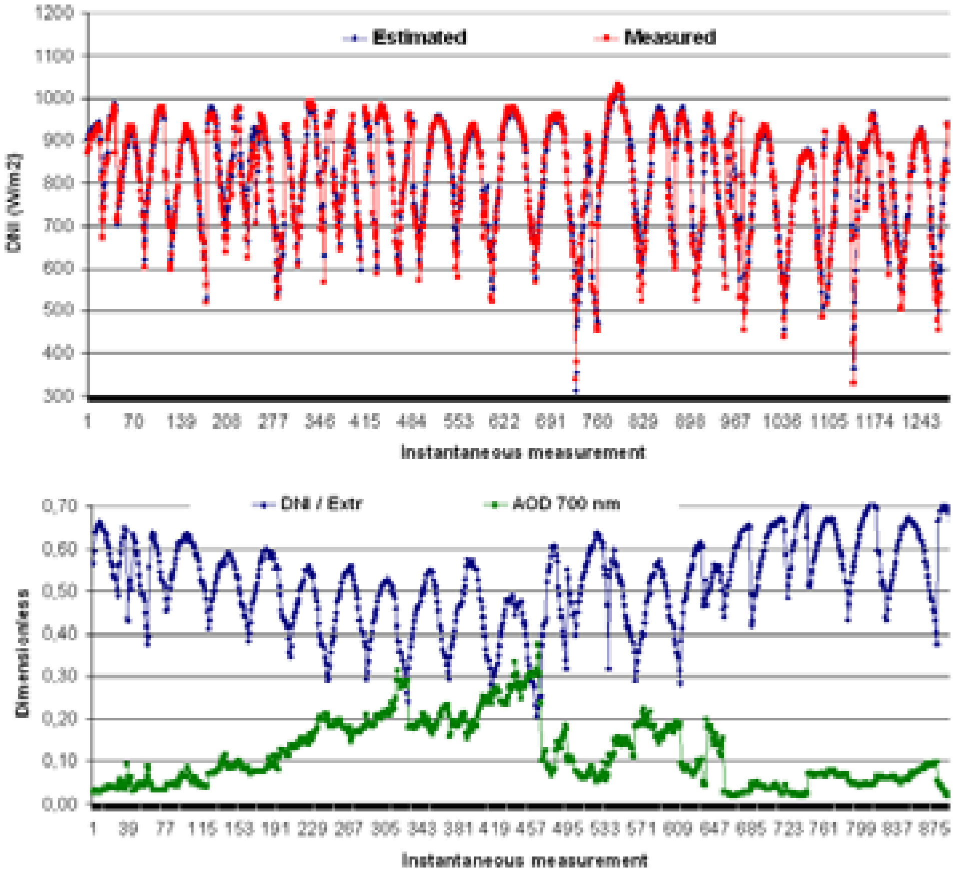

Fig. 2. Solar irradiation forecasting spatial and temporal scales and their typical target applications.

Fig. 2 (bottom) shows the relative influence of AOD at 700 nm on DNI (normalized with extraterrestrial irradiation, EI). A significant drop in the DNI to EI ratio is observed at higher AOD, showing the influence of this parameter on DNI availability.

Empirical Cumulative Distribution Functions (ECDF) of measured and estimated series were compared, with excellent results (Fig. 3, left). Fig. 3 (right) shows a scatter plot of measured and estimated series. Fit is more accurate at higher DNI. Furthermore, data seem to be grouped in two categories (plotted in blue and red), each of which is defined by a linear fit. Classification of data in one of these categories could improve the fit of estimated and measured data.

Fits between global horizontal (Gh) irradiation measurements and estimations are also quite good, as shown in Fig. 4. In this case, a few points (compared to the general trend) are observed which increase both the fitting line slope and scatter. Again, the identification of these points could lead to an improvement of global irradiation estimation with AOD measurements.

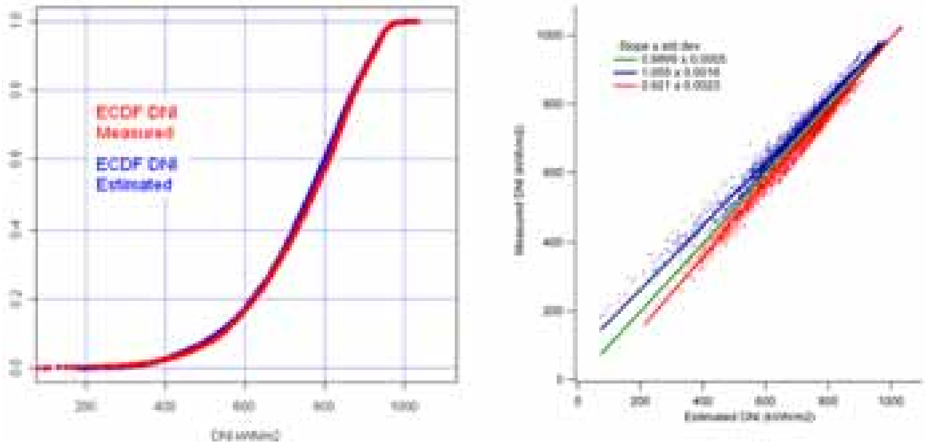

Fig. 3. Left, ECDF of measured and estimated DNI under clear sky conditions; right, scatter plot of measured vs estimated DNI measured under clear sky conditions.

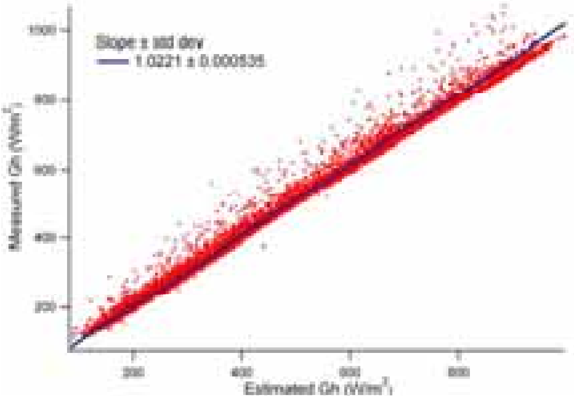

Fig. 4. Scatter plot of measured vs estimated global horizontal irradiation measured under clear sky conditions.

3.2. DNI estimation through satellite-derived AOD

Clear sky model estimation with AOD satellite-derived data can be a powerful tool for characterizing the DNI in locations where there is no measured AOD. In this case, it was necessary to use the clear sky model in [3], due to the information provided by Giovanni.

A preliminary comparison between measured and estimated DNI derived from clear sky models using AOD data provided by Giovanni was also carried out. DNI calculated from Giovanni AOD data was found to be significantly underestimated compared to calculations with AERONET AOD data (which are very accurate). This underestimation can be seen on both the daily (Fig. 5, top left) and hourly scales (Fig. 5, bottom). The difference between the two daily DNI series is almost 8% (Fig. 5, top right). These results show inaccurate estimation of DNI using a clear sky model with satellite-derived AOD.

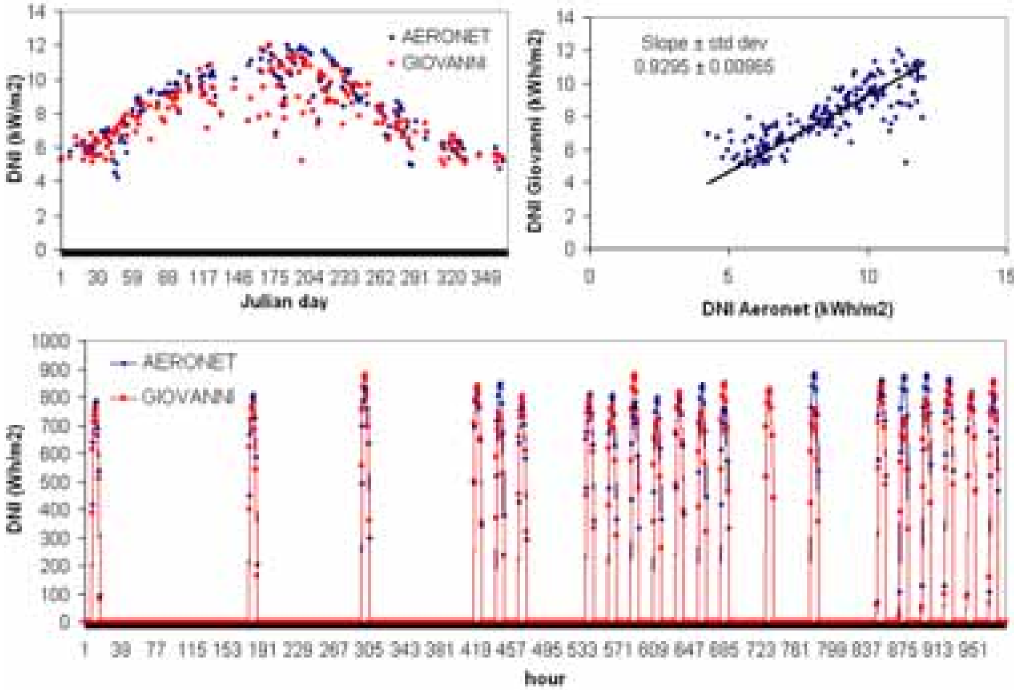

Fig. 5. Top left, daily DNI (clear sky conditions), calculated from AOD data provided by AERONET and Giovanni. Top right, scatter plot of daily DNI (clear sky conditions) estimated from AOD data provided by AERONET and Giovanni. Bottom, hourly DNI (clear sky conditions) estimated from AOD data provided by AERONET and Giovanni.

3.3. DNI prediction using forecast AOD

The BSC-DREAM8b model is used to predict both clear sky conditions and AOD. The information provided requires the use of the clear sky model presented in [3], as data required by the clear sky model in [2] are not supplied.

Under clear sky conditions, a prediction of solar irradiation using recent (5 days before at most) measurements (recorded at the same optical air mass and AOD) has been demonstrated to be more accurate than a clear sky model predictions. Notwithstanding, prediction based on clear sky models has proven to be more accurate than a prediction based on the use of recent measured data when AOD are different on those days. Therefore, combined use of the measurement and estimation approaches is proposed for forecasting clear sky solar irradiation, as shown in Fig. 6:

Fig. 7 shows DNI measurements (red line), DNI forecasts with a clear sky model (blue line), and DNI forecasts using the procedure described below (green line):

Day 1. - There is good agreement between measurements and predictions.

Day 2. - Because of a change in forecast AOD, DNI predicted by the clear sky model increases, fitting the measured data. In this case, the procedure proposed uses the data provided by the clear sky model as the DNI prediction.

Day 3. - As AOD on the second day is the same as predicted for the third day, the proposed procedure uses AOD data measured on the second day as the DNI prediction. In this case, measurements and both predictions are very similar.

Day 4. – The sky is not clear.

Day 5. – After a day without clear sky, the proposed procedure uses the data provided by the clear sky model as a DNI prediction, with poor fit of measured data.

Day 6-8. - From the sixth to the eighth day, the proposed procedure uses the data measured on the day before as the DNI prediction. In these cases, the proposed procedure provides a better fit than the one provided by the clear sky model.

Day 10. – As the AOD prediction changes, the proposed procedure uses the data provided by the clear sky model as the DNI prediction. On this day, both procedures provide a good prediction.

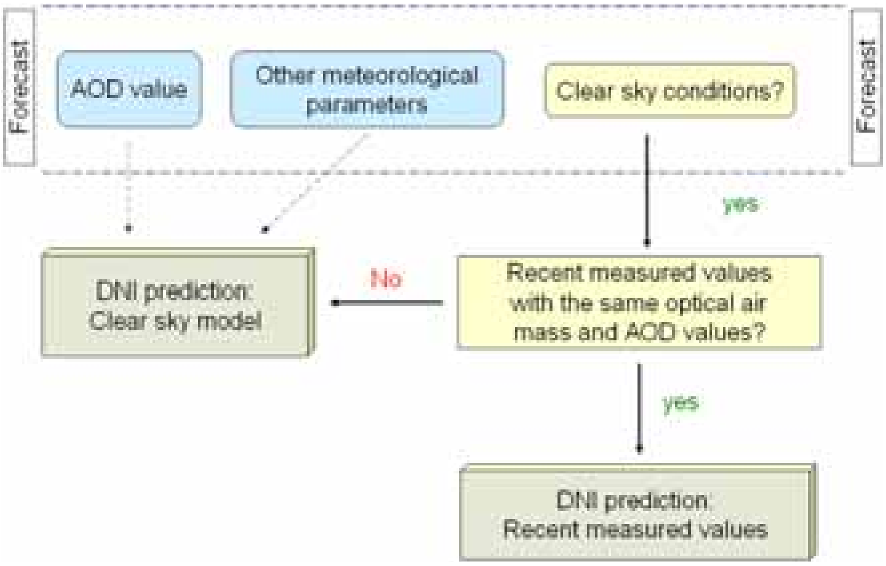

Fig. 6. Flow diagram for clear sky DNI prediction.

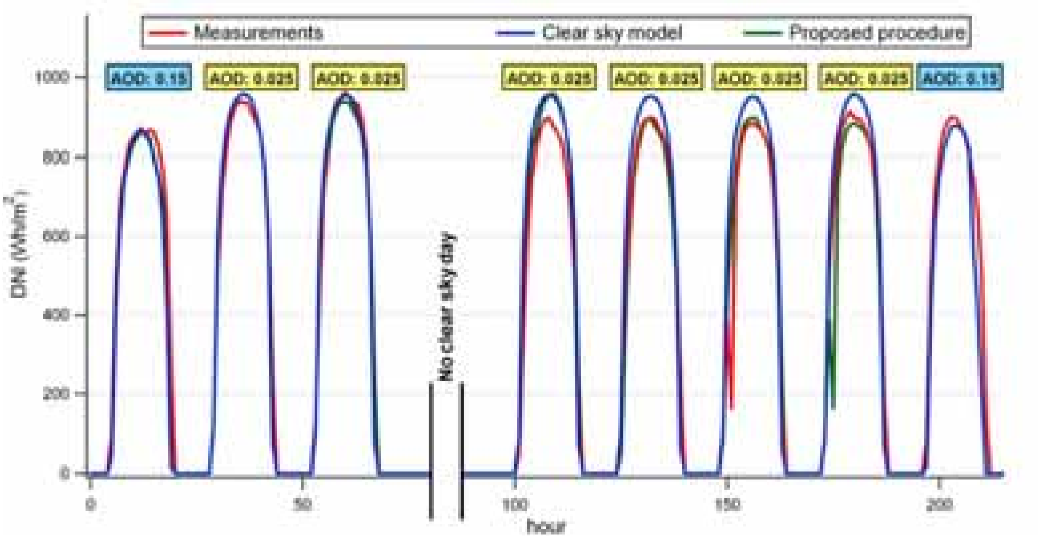

Fig. 7. , Measured DNI (red line), DNI forecast with a clear sky model (blue line), and DNI forecast using the procedure described (green line) under clear sky conditions.

5. Conclusions

Accurate estimations of Direct Normal Irradiance (DNI) have been made with a clear sky model using Aerosol Optical Depth (AOD) measurements. Estimations of DNI with this model can be used to confirm the goodness of DNI measurement due to its accuracy and simplicity, and given the inherent difficulty in DNI measurement. The clear sky model can also provide an accurate estimation of global irradiation, unfortunately, measured AOD is required, as estimation of DNI by means of satellite-derived AOD data has been found to be inaccurate.

A simple and effective method is presented to predict DNI under clear sky conditions from AOD and cloud cover forecasts, by the combined use of DNI measurement and estimation approaches.

References

[1] E.D. Dunlop, L. Wald, M. Suri (2006). Solar Resource Management for Electricity Generation from Local Level to Global Scale, Nova Science Publishers, New York.

[2] P. Ineichen. Solar Energy, 82 (2008), 758-762

[3] P. Ineichen, R. Perez. Solar Energy 73 (2002), 151–157

[4] R.E. Bird, R.L. Huldstrom. Trans. ASME J. Sol. Energy Eng., 103 (1980) 182-192