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DNI estimation procedures for the assessment of solar radiation availability in concentrating systems

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Abstract

DNI (Direct Normal Irradiance) is the resource utilized by solar concentrators. Besides, the determination of *DNI* is needed in the models for the estimation of global irradiance on tilted planes, which is the input to flat-plate systems. This paper describes a study of different estimation procedures for the assessment of the *DNI*, using experimental data with a time scale of 1 min, taken at two different latitudes. The analyzed approaches include measuring techniques and models. The results show that the different estimation methods can lead to quite different conclusions when comparing the solar radiation availability in concentrating and flat-plate systems and this can affect the energy and economic evaluations. Based on the experimental analysis, indications for reducing the uncertainty in the estimation of *DNI* are discussed.

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1. Introduction

The development of solar concentrators calls for the assessment of *DNI* (Direct Normal Irradiance). Besides, *DNI* plays a role in the use of transposition models for the estimation of the global irradiance on tilted planes, which is utilized by flat-plate systems. Such models convert the global irradiance on the horizontal plane to the global irradiance on the tilted plane and their use requires transposing separately the direct and diffuse radiation components. Since direct radiation has a geometric behavior, the horizontal direct irradiance comes from *DNI* multiplied by the cosine of the zenith angle. Therefore, the assessment of *DNI* is crucial for the study of both concentrating and flat-plate solar systems.

While accurate datasets of global horizontal irradiance are available for many sites, still efforts are required to fully characterize the *DNI* resource.

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Nomenclature

DHI	diffuse horizontal irradiance (W/m^2)
DNI	direct normal irradiance (W/m^2)
GHI	global horizontal irradiance (W/m^2)
$H_{2\text{-axes,conc}}$	monthly irradiation available for a 2-axes concentrating system (J/m^2)
$H_{2\text{-axes,fp}}$	monthly irradiation available for a 2-axes flat-plate system (J/m^2)
k_t	clearness index
k_t'	clearness index modified by Perez et al. [16]
u	standard uncertainty (W/m^2)
W	precipitable water (cm)
Δk_t	variability of clearness index as defined in Skartveit et al. [15]
$\Delta k_t'$	stability index as defined by Perez et al. [16]
% ΔH	$(H_{2\text{-axes,fp}} - H_{2\text{-axes,conc}}) 100 / H_{2\text{-axis conc}}$ (%)
θ_z	zenith angle ($^\circ$)
<i>Other subscripts</i>	
cal	calculated with estimation procedure
exp	experimental
meas	measured with pyrheliometer
ref	reference estimation procedure

The reference instrumentation for the measurement of *DNI* is composed of a thermopile pyrheliometer installed on a sun tracker. This measuring system is quite expensive mainly due to the tracker. Another possibility is to indirectly derive *DNI* from the measurements of global and diffuse horizontal irradiance. The diffuse irradiance is measured with a shaded pyranometer and the best way is to occult the solar disk with a ball driven by a sun tracker. A cheaper and common technique uses a shadow band, which screens the pyranometer along the day. In this case only a manual adjustment of the band is required each few days as the declination changes, but the measured irradiance has to be corrected, because the band blocks also a part of diffuse radiation. The main problem in the indirect evaluation of *DNI* is that pyranometers can be affected by several sources of uncertainty, which should be properly considered, as discussed by Gueymard and Myers [1].

When only the horizontal global irradiance is known, *DNI* can be estimated by using separation models (semi-physical and empirical). In their basic form such models are simple, because they have as an input the clearness index, which is the ratio of global horizontal irradiance to extraterrestrial horizontal irradiance. They can be used in every site and with different time resolutions, depending on the characteristics of the dataset of global horizontal irradiance. However, due to their empirical derivation, these models need to be verified in many sites with different sky and climatic conditions. Another critical

point is that they were developed using mainly hourly irradiance measurements. Since datasets with time resolution better than one hour are more adequate for design and simulation of concentrating systems (Meyer et al. [2]), there is need to assess their performance in the estimation of sub-hourly *DNI*. Short-term *DNI* data are difficult to model, because they are more sensitive to the variability of the sky conditions and in fact high scattering can be found when comparing measurements with model predictions, as shown for example by Gueymard [3], Padovan and Del Col [4].

This paper addresses the assessment of estimation procedures of *DNI*, which include indirect evaluation from measurements of global and diffuse horizontal irradiance and use of semi-physical/empirical models. The capability of generating 1 min time series of *DNI* and the accuracy in the estimation of the monthly irradiation are tested. Due to their flexibility semi-physical and empirical models are looked with interest by engineers and designers of solar energy installations. Moreover, a combination of ground measurements and modeling data is often used in development and validation of databases (Remund and Muller [5]). Since measurements of global and diffuse irradiance have good accessibility and availability, the present paper aims at clarifying to what extent such data can be used for deriving *DNI* time series.

2. Solar radiation measurements and uncertainty analysis

Two experimental datasets of solar irradiance are used for the present study. One is collected in Padova (45.4°N, 11.9°E), northern Italy, while the other is collected in Trisaia (40.2°N, 16.6°E), southern Italy. The two sites cover a wide range of climatic and sky conditions. Italy is a favorable site for solar energy installations; particularly Trisaia is interesting for solar concentrating applications.

Data taken at Padova include global horizontal irradiance, measured with a CMP22 Kipp&Zonen pyranometer, *DNI*, measured with a CHP1 Kipp&Zonen pyrliometer mounted on a EKO Instruments sun tracker, and diffuse horizontal irradiance, measured with a CM11 Kipp&Zonen pyranometer placed under a shadow band. Due to the use of the shadow band, the values of diffuse irradiance are corrected with the model by LeBaron et al. [6]. Data taken at Trisaia include global horizontal irradiance, measured with an EKO MS-802 pyranometer, *DNI*, measured with an EKO MS-56 pyrliometer and diffuse horizontal irradiance, measured with an EKO MS-802 pyranometer shaded with a ball driven by the sun tracker. Pyrliometers are first class instruments and pyranometers are secondary standard classified, according with ISO 9060: 1990 [7]. In both stations, irradiance measurements are taken with a time step of 5 s and then the minimum, average, maximum and standard deviation are stored every minute. The status of the instrumentation is periodically checked to avoid any sources of inaccuracy.

The evaluation of the *DNI* estimation procedures requires determining the uncertainty of the irradiance measurements. The uncertainty analysis, here adopted, is based on the procedure described by Padovan and Del Col [8], who show how apply the method by ISO, Guide to the Expression of Uncertainty in Measurement [9] to the irradiance measurements with thermopile pyranometers. Reda [10] also proposed a method for calculating the uncertainty in measuring shortwave solar irradiance, which substantially agrees with that illustrated by Padovan and Del Col [8].

Thermopile radiometers are characterized by a specific sensitivity (ratio of output voltage to irradiance), as obtained from the calibration. However, pyranometers and pyrliometers operate at different conditions as compared to those occurring in calibration, thus further sources of uncertainty should be added to the calibration uncertainty. Table 1 reports a list of the uncertainties, which can affect the present instruments: all the uncertainties, reported in the table, are type B components and are characterized by a rectangular distribution. The thermal offset error is usually divided in the contribution due to the infrared exchange between the pyranometer and the sky (zero offset A) and the part due to the change in the temperature of the body of the instrument (zero offset B). Zero offset A is not reported in

Table 1, but it is treated separately, because it provides a systematic underestimation of irradiance. In the present analysis the thermal offset A has been experimentally evaluated, by analyzing night time measurements and by running specific diurnal tests in which the dome of the pyranometers is covered. A posteriori correction of measurements has been done. In particular, in the case of the data measured at Padova, it was found that CM11 has a higher thermal offset as compared to CMP22 and this result agrees with the different overall accuracy of the two pyranometers, which can be also observed in Table 1. Moreover, according with other independent observations, such as Gueymard and Myers [1], the measured thermal offset is higher with clear sky conditions. Data of global and diffuse irradiances measured in Trisaia, instead, have been corrected by using the observations of night time thermal offset.

The overall uncertainty of irradiance data is obtained by combining the uncertainty due to the calibration with the components reported in Table 1 and the uncertainty of the acquisition system. For diffuse irradiance the contribution of the directional response has been neglected. Moreover, no uncertainty is attributed to the correction by LeBaron et al. [6]. The statistical type A uncertainty has been also calculated and taken into account. However, as discussed in Padovan and Del Col [8], its contribution is negligible with clear and overcast skies, which represent stationary conditions.

When indirectly derived, DNI is obtained as:

$$DNI_{cal} = \frac{GHI - DHI}{\cos(\theta_Z)} \quad (1)$$

where GHI and DHI are the global and diffuse horizontal irradiance, respectively, and θ_Z is the zenith angle, which is the incidence angle of direct radiation on the horizontal plane. In this case, the uncertainty of DNI_{cal} is:

$$u_{DNI_{cal}} = \frac{\sqrt{(u_{GHI})^2 + (u_{DHI})^2}}{\cos(\theta_Z)} \quad (2)$$

where u_{GHI} and u_{DHI} are the standard uncertainties of the global and diffuse horizontal irradiances, respectively.

To ensure the quality of the data, the agreement between the pyranometers, which are used to measure the global and diffuse irradiances, has been checked: both pyranometers are set up to measure the global irradiance on the horizontal plane in some days test. This check covers different periods of the year to include a wide range of zenith angles and sky conditions. Although the thermal offset has been corrected, with clear sky some disagreement has been observed between CM11 and CMP22, which has displayed a dependence on the zenith angle.

Table 1. Uncertainty sources in pyranometers and pyrhemometers.

Uncertainty source	CHP1	CMP22	CM11	MS-56	MS-802
Directional response	-	$\pm 5 \text{ W/m}^2$	$\pm 10 \text{ W/m}^2$	-	$\pm 10 \text{ W/m}^2$
Temperature response	$\pm 0.5\%$	$\pm 0.5\%$	$\pm 1\%$	$\pm 0.5\%$	$\pm 1\%$
Non-linearity	$\pm 0.2\%$	$\pm 0.2\%$	$\pm 0.5\%$	$\pm 0.5\%$	$\pm 0.5\%$
Spectral response	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$	$\pm 1\%$	$\pm 1\%$
Zero offset B	$\pm 1 \text{ W/m}^2$	$\pm 1 \text{ W/m}^2$	$\pm 2 \text{ W/m}^2$	$\pm 1 \text{ W/m}^2$	$\pm 2 \text{ W/m}^2$

By assuming CMP 22 as the reference pyranometer, a correlation has been developed to correct CM11. Such correction has been tested against independent data and complete agreement between CM11 and CMP22 has been found.

Similarly, also for Trisaia test site, the pyranometers used for measuring global and diffuse solar irradiances have been checked. The check has been performed by comparison with a reference secondary standard CMP11 pyranometer, calibrated by a European accredited laboratory. The in site calibration has been performed outdoor according to ISO 9847 - Method Ia - [11] in a wide range of zenith angles, sky and ambient temperature conditions. This calibration procedure has allowed correcting the sensitivity factors of the pyranometers used to measure the different components of solar irradiance during the monitoring period. Such corrections have been tested for a significant time period during which a complete agreement between the CMP11 reference pyranometer and the EKO MS-802 pyranometers has been found.

3. Assessment of DNI estimation procedures

3.1. Estimation procedures

The first type of estimation procedure derives *DNI*, by means of Eq.(1), from the measurements of global (*GHI*) and diffuse (*DHI*) horizontal irradiance. The second type is based on separation models, which provide *DNI* or *DHI*; if the model provides *DHI*, *DNI* is then obtained with Eq.(1). Table 2 reports the separation models analyzed in this study: Erbs et al. [12], Maxwell [13], Perez et al. [14], Skartveit et al. [15], DIRMX and DIRINT (both by Perez et al. [16]). Perez et al. [14] is a simple modification of the Maxwell [13] model, which is multiplied by a correction function, empirically obtained from a large pool of data. Skartveit et al. [16] consider also the variability of the clearness index as prediction variable. The models DIRMAX and DIRINT (Perez et al. [16]) are more complete and they use also the precipitable water; however, they can work even when not all the input variables, as listed in Table 2, are available. The term k_t' is the modified clearness index as defined in Perez et al. [16].

3.2. Estimation accuracy of DNI time series

In Fig. 1, the daily trend of *DNI*, observed in a summer (graph on the left) and a winter (graph on the right) day in Padova, is plotted as a function of the local time: the two sets, reported in each graph, correspond to the *DNI* measured with the pyrheliometer and the *DNI* calculated from the global and diffuse measured irradiances. The bands of experimental uncertainty are also drawn. In both days the experimental uncertainty of the measured *DNI* is $\pm 2.5\%$. Close agreement between calculated and measured *DNI* is found in the summer day.

Table 2. Separation models for *DNI* estimation.

<i>Model</i>	<i>Input variables</i>	<i>Model output</i>
<i>Erbs et al. [12]</i>	k_t	<i>DHI</i>
<i>Maxwell [13]</i>	k_t, ϑ_z	<i>DNI</i>
<i>Perez et al. [14]</i>	$DNI_{Maxwell}, k_t, \vartheta_z$	<i>DNI</i>
<i>Skartveit et al. [15]</i>	$k_t, \vartheta_z, \Delta k_t$	<i>DHI</i>
<i>DIRMAX, DIRINT [16]</i>	$DNI_{Maxwell}, k_t', \vartheta_z, \Delta k_t, W$	<i>DNI</i>

In that case, at solar noon the uncertainty of DNI_{cal} is $\pm 4\%$, but it increases in first morning and late afternoon due to the effect of the directional response, reaching $\pm 7\%$ at around 18:00 local time. In the winter day, the indirect method overestimates DNI more than in the summer day and on average its uncertainty is higher because of the higher zenith angles that characterize the sky conditions. For example, at solar noon the uncertainty of DNI_{cal} is $\pm 5\%$, but it increases up to $\pm 10\%$ at the ends of the day, when higher values of zenith angle occur. However, DNI_{meas} and DNI_{cal} are in agreement within their range of uncertainty.

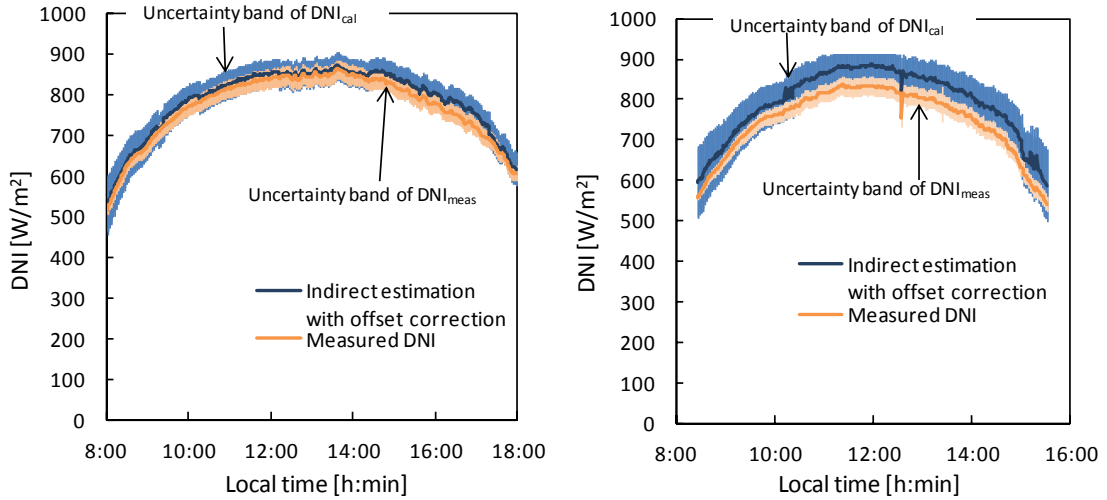


Fig. 1. DNI vs. local time for a clear sky day in Padova in summer (left) and winter (right). The data points and the experimental uncertainty bands are plotted.

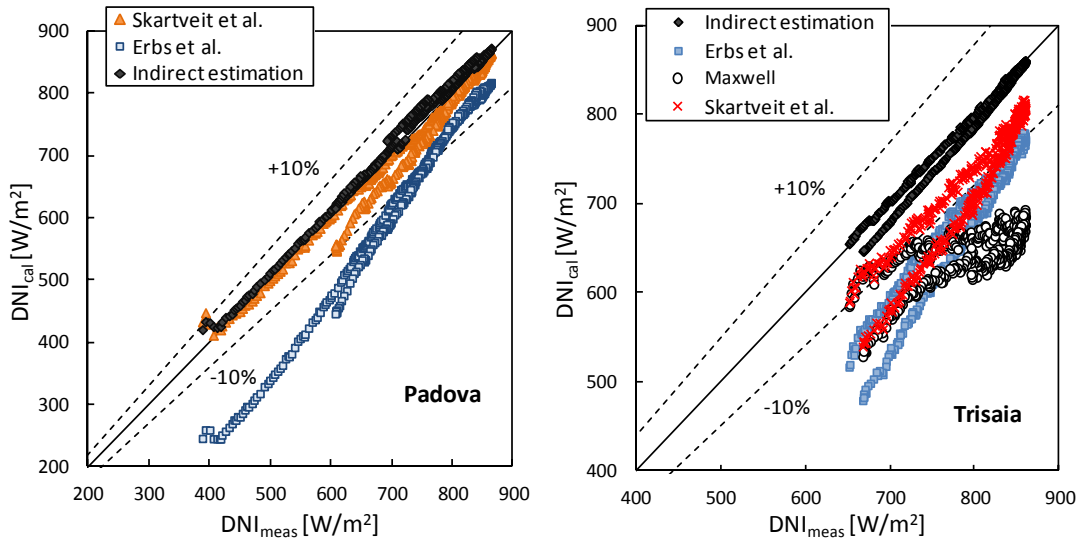


Fig. 2. Calculated DNI vs. measured DNI for a summer day with clear sky: Padova (left) and Trisaia (right).

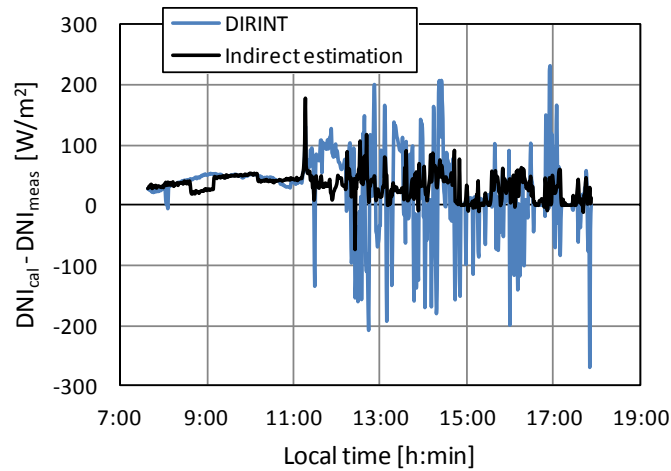


Fig. 3. Calculated DNI vs. measured DNI for a partially cloudy day in Padova.

Fig. 2 shows the prediction accuracy of estimation procedures for a summer day with clear sky in Padova (left graph) and Trisaia (right graph). For the sake of clearness, only some representative procedures are shown in the graphs. As it can be seen from the graph, the indirect estimation allows good agreement with *DNI* data, provided that the thermal offset is corrected. If it were not corrected, the indirect procedure would overestimate *DNI*, because, as discussed in Sec. 2, the measurement of the horizontal diffuse irradiance is affected by a thermal offset higher as compared to the global horizontal irradiance and this results in the overestimation of *DNI* when Eq.(1) is applied. The importance of the thermal offset correction increases in the winter days, due to higher zenith angles and the more severe effect of the thermal offset: in that case, if the thermal offset is not corrected, the calculated values of *DNI* may be out of the experimental uncertainty bands of measured and indirectly estimated *DNI*.

With reference to the data for Padova site in Fig. 2, Skartveit et al. [15] and DIRINT [16] (not shown in the graph) agree with the measured *DNI* within $\pm 10\%$. The Erbs et al. [12] correlation estimates within $\pm 10\%$ the high *DNI* values, but it becomes inaccurate when *DNI* decreases, both in the morning and afternoon. One reason may be the absence of the zenith angle as prediction variable.

At Trisaia site, the indirect estimation procedure shows high agreement with measured *DNI*, due to the use of the tracking ball in the measurement of diffuse horizontal irradiance. The separation models, instead, do not perform satisfactorily.

In Fig. 3 the accuracy of the estimation procedures is tested with sky variability: in the first part of morning, sky conditions are stable and both the indirect procedure and DIRINT [16] model show a stable performance, overestimating *DNI* by around 3% to 5%. When sky variability begins, both estimation methods show a higher scattering, particularly the DIRINT [16] model.

4. Prediction of solar radiation availability in concentrating and flat plate systems

This section discusses how the *DNI* estimation procedures can affect the comparison between the irradiation availability of different solar energy systems. For this analysis the month of august 2012 has been selected: it is a summer month, interesting for energy production at the present latitudes. The

parameter $\% \Delta H$ is defined to compare the solar resource availability on flat-plate and concentrating systems:

$$\% \Delta H = \frac{H_{2\text{-axes,fp}} - H_{2\text{-axes,conc}}}{H_{2\text{-axes,conc}}} 100 \tag{3}$$

where $H_{2\text{-axes,fp}}$ and $H_{2\text{-axes,conc}}$ are the monthly irradiations available on a 2-axes tracking flat-plate system and a 2-axes tracking concentrating system, respectively. The monthly irradiation available to the concentrating system can be obtained by integrating the DNI over one month while the monthly irradiation on the flat plate can be calculated as the integral of the global irradiance on the tracking plane. Data characterized by zenith angles higher than 80° are not used here to calculate the monthly irradiations, because of the high predicting uncertainty that models display at such conditions.

As a first step, an optimal procedure is established to assess the reference irradiation for each type of solar system. For concentrating systems, since the DNI is directly measured, the reference irradiation is given by the time integral of DNI measured with the pyrheliometer. For tracking flat-plate systems, since the global irradiance on the tilted plane is not directly measured, the reference irradiation is obtained from the measurements of GHI and DNI and using the HDKR model (Reindl et al. [17]) to convert irradiance from the horizontal to the tilted plane. The HDKR [17] model is here selected as the optimal model, because it has shown high accuracy in the prediction of global irradiance when varying plane orientation and inclination and particularly with planes normal to the solar beam, as discussed in Padovan and Del Col [8], Del Col et al. [18].

Several estimation procedures have been tested and compared in Fig. 4 (for the site of Padova). For each procedure, at least two irradiance components are needed: one parameter is the experimental global irradiance on the horizontal plane while the second one may come from experiments (DNI or D_h) or from models. For example, the first estimation procedure uses the experimental values of GHI and DNI , while the second procedure uses the experimental values of GHI and DHI . When the only experimental value is G_h , separation models are applied to calculate DNI . In this calculation the DIRMAX [16] and DIRINT [16] models are applied without using the precipitable water as an input parameter. For the flat-plate system the tilted irradiance is also calculated with the isotropic Liu and Jordan [19] model.

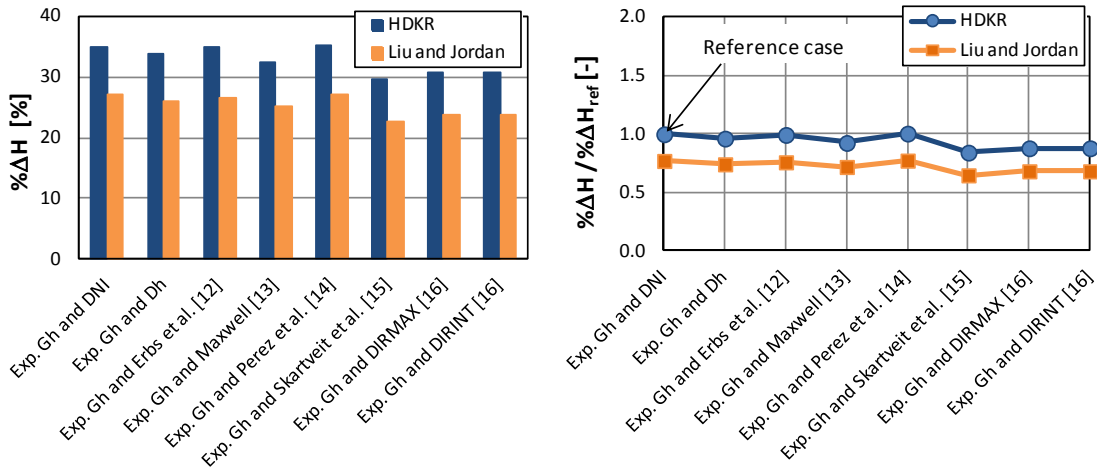


Fig. 4. Percentage difference between monthly irradiation available on a flat-plate system and a concentrating system when different estimation methods are applied (left). Accuracy of estimation methods as compared to the reference procedure, which is based on measurements of GHI and DNI and the HDKR [17] transposition model (right). Site: Padova, month: August.

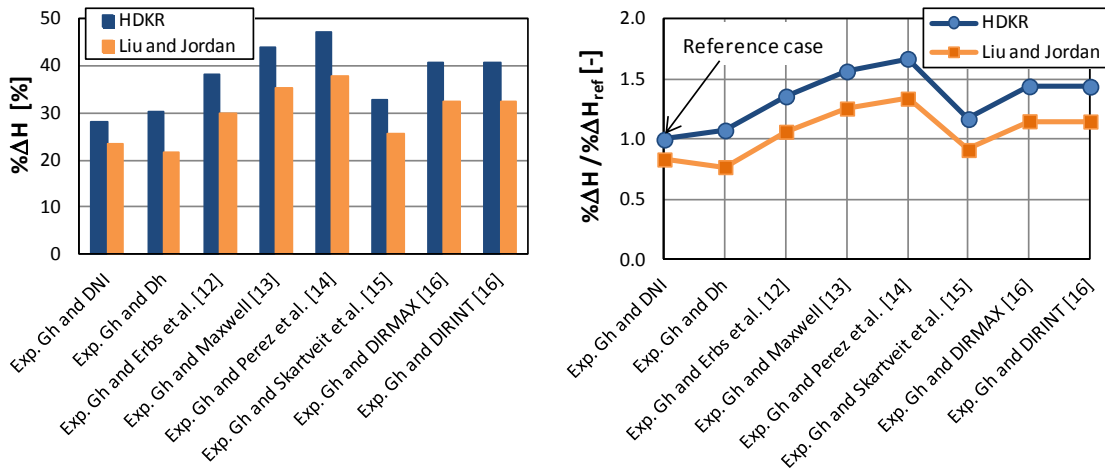


Fig. 5. Percentage difference between monthly irradiation available on a flat-plate system and a concentrating system when different estimation methods are applied (left). Accuracy of estimation methods as compared to the reference procedure, which is based on measurements of *GHI* and *DNI* and the HDKR [17] transposition model (right). Site: Trisaia, month: August.

As expected the difference in the available irradiation for the two systems decreases when using the Liu and Jordan [19] model and this may be explained knowing that such model tends to underestimate the tilted irradiance, as discussed by Padovan and Del Col [4], Del Col et al. [18]. Moreover, the selection of the transposition model seems to affect the results more significantly as compared to the selection of the *DNI* estimation procedure.

The same analysis is reported in Fig. 5 for the site of Trisaia. As already observed for Padova, the use of the transposition model by Liu and Jordan [19] reduces the difference between solar radiation availability on flat-plate and concentrating systems. However, here, differently from the results in Fig. 4, the selection of the *DNI* estimation procedure plays a significant role.

5. Conclusions

This study has addressed the analysis of *DNI* estimation procedures for the assessment of the solar radiation availability in concentrating systems. The results have shown that the indirect derivation of *DNI* from measurements of *GHI* and *DHI* can lead to accurate estimations even when diffuse irradiance is measured with a shadow band, provided that the systematic error due to the thermal offset is evaluated and corrected. Clearly, the experimental uncertainty associated with this procedure increases at irradiance conditions characterized by high zenith angles.

Separation models have provided quite different results for the two sites under investigation. In Padova, some models, such as Skartveit et al. [15] and DIRINT [16], have shown a good accuracy in generating clear sky time series of *DNI*. At Trisaia site, separation models have shown significant inaccuracy. The accuracy of the models decreases significantly under variable sky conditions.

When estimating the monthly direct normal irradiation, long term effects reduce the errors provided by the *DNI* models. The use of an anisotropic model, such as HKDR [16], is recommended when one would compare the irradiation availability on concentrating and flat-plate systems. However, from Fig. 5 it can be observed that long term compensation effects may lead to satisfactory results even when using the less accurate Liu and Jordan [19] model. However, there is need for a more comprehensive investigation of *DNI* models, that should be based on a systematic analysis of the sky and atmosphere conditions.

Acknowledgements

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