How applicable are standard Solar Irradiation Maps?  
Insights from Case Studies

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Abstract

Solar irradiance maps provide a fast means to assess the quantity and nature of the solar power obtainable at a given site. They are produced by a range of scientific or commercial entities through applying aggregated site conditions to specific solar irradiance models. Their verification through on-site irradiance measurements is only possible in limited cases due to the frequent scarcity of ground-based data. We test the degree of accuracy of a variety of irradiance maps in two regions: western China and southern Africa. While in the majority of cases the differences between the map and site data are no larger than the typical inter-annual variance, inconsistencies were detected in some cases. We propose that a significant factor contributing to incorrect map values is likely to be the flawed recognition and parameterisation of aerosols. In particular, we find that some methods used for determining irradiance over the drier southern African sites have overestimated the Linke turbidity there. We suggest that this may equally account for some inaccurate irradiance values presented for western China.

1. Introduction

Solar irradiation maps provide useful first-order approximations of the solar energy potential at a specific location, and are utilized extensively from exploratory studies to pinpoint potential solar power station sites to estimating the solar energy yield in buildings.

A number of resources are available that generate or distribute solar maps and databases. The originators of these maps include:

- the Solar and Wind Energy Resource Assessment (SWERA) database [1]
- the Photovoltaic Geographic Information System (PVGIS) [2]
- The South African DME/Eskom/CSIR map [6]

The first-mentioned (SWERA) maps may be generated by several contributors (e.g. the United States NREL and the German DLR), while the last-mentioned is a solar map that was jointly produced by the
South African ministry of Minerals and Energy, the electricity provider Eskom and the Council for Scientific and Industrial Research in 2001, and is widely referred in that country’s energy sector.

It should immediately be noted that some of these products neither claim exceptional quality nor detailed resolution, and often freely available maps are promotional material that are deliberately blurred to protect a company’s intellectual property. Nonetheless, even these are widely in use, and are frequently quoted in solar project development proposals and scientific studies.

Solar maps are usually developed through the inter- and extrapolation of ground-recorded irradiance values at specific sites or through the processing of satellite images (e.g. [7-8]). The various datasets match each other well in those parts of the world where they have been validated against ground-based measurements. For example, the PVGIS dataset is based on detailed calculations and models that had proven to be very effective in describing European solar irradiation conditions [9]. Outside the temperate mid-latitudes their accuracy is however less certain.

In this paper we seek to evaluate the general precision of solar irradiance maps by comparing the maps produced by different developers with each other, as well as with other equivalent forms of data when available (e.g. ground-based data). We do this by investigating two specific parts of the world that have been earmarked for the expansion of solar energy development capacity.

2. Irradiance parameters

2.1. Physical formalism

Reference will be made in this paper to different modes of measuring solar irradiance. In particular, solar maps usually plot either the global horizontal irradiance (GHI), i.e. the total radiation energy (solar beam plus reflected sky light) collected per unit area in a particular time interval by a horizontal flat surface, or the direct normal irradiance (DNI), i.e. the corresponding quantity measured by a surface facing the Sun, excluding the sky radiation. These quantities are related by the formula

\[ G = I \cos \theta + D, \]

where \( G \) is the GHI, \( I \) is the DNI, \( D \) is the diffuse (sky) irradiance and \( \theta \) is the angle between the solar beam and the vertical (see, e.g. [10]).

These parameters have contrasting significance depending on the solar energy technology; concentrated solar power technologies are only sensitive to the solar beam, and hence their efficiencies are based on the DNI values. Photovoltaic panels are however in a position to process all incident radiation, and thus the GHI values are critical to evaluate their overall performance. Of course complications arise due to the tilting of the solar light receiver and its inability in many technologies to align itself to the solar beam, but that aspect has been extensively studied and reported on in the literature, and will not be discussed further here.

A second physical aspect that is critical to most procedures to construct solar irradiance maps is how attenuation of light is parameterised and processed. In the case of a monochromatic beam of light, the transmission through the atmosphere is well approximated by the relation

\[ F(\lambda) = F_0(\lambda)e^{-\tau(\lambda)\sec \theta}, \]
where $F$ is the beam power received per unit area and wavelength interval and $r$ is referred to as the optical depth (e.g. [11]). $F_0$ is the value of $F$ at the top of the atmosphere. The irradiance thus becomes

$$I = \int F(\lambda) d\lambda = \int F_0(\lambda)e^{-r(\lambda)\sec \theta} d\lambda.$$  \hspace{1cm} (3)

In view of the very complex wavelength dependence of the optical depth, which is also a function of the aerosol and greenhouse gas concentrations, this integral cannot be solved analytically. Hence the DHI incorporates a tricky $\cos \theta$ factor that needs to be described through empirical formulation.

In most cases solar irradiance measurements are carried out with standard pyranometers that are not able to provide information regarding the spectrum of the incident light. As the degree of incident light loss is however an important aspect of the study of irradiance, a parameter analogous to the optical depth, introduced by Linke as early as 1922, has come into very wide usage (see [12] for a deeper discussion). It is defined by the equation

$$I = I_0 e^{-\Lambda \delta \sec \theta},$$  \hspace{1cm} (4)

where $I_0$ is the solar beam intensity at the top of the atmosphere ($\sim 1370 \text{ W/m}^2$), and $\Lambda$ and $\delta$ are referred to as the Linke turbidity and integral Rayleigh optical depth respectively.

Unfortunately, because of the factors alluded to following equation 3, both $\Lambda$ and $\delta$ are partly dependent on the solar beam angle $\theta$. To make matters worse, the integral in equation 3 is for practical purposes (especially because of limited detector sensitivity) only applied to a specific wavelength range. In essence this means that the Linke turbidity is also a function of the chosen interval of integration. Yet it is this very parameter that is ingrained in many of the irradiance models used in the development of solar radiance maps.

### 2.2. Units to quantify solar irradiance

Adding to the confusion in map interpretation is the variety of units used to quantify irradiance, and it is worthwhile recapping the relationships between these. Energy may be measured in Joules (the SI unit favoured by scientists), but energy practitioners and electrical engineers are more likely to quantify this parameter in kWh (where 1 kWh = $3.6 \times 10^6$ J = 3.6 MJ). Irradiance is also sometimes quoted in terms of kWh per day or kWh/m$^2$ per day, which must then be converted to yearly averages by multiplying the values by 365.24. In other instances the irradiation is given in terms of (long-term average) power (i.e. in W, corresponding to J/s) rather than energy. In that case 1 W/m$^2$ equates to 31.557 MJ per year.

### 3. Case Study 1 – Western Peoples Republic of China

#### 3.1. The region

The western part of the People’s Republic of China considered in this paper is a generally dry region with extreme seasonal temperature fluctuations. Its altitude ranges from below sea level at the Turpan depression to the top of the Himalaya Mountains. Administratively it consists of the Xinjiang and Tibet autonomous regions and parts of Qinghai and Gansu provinces.

As elsewhere in the world, interest in solar energy usage has grown significantly in China and with it the goal of an accurate characterization of the solar potential. In addition, there have been concerns about the high levels of air pollution in the industrial centres, particularly in Urumqi, the largest city in...
the area studied. The drive to explore clean forms of energy has led to initiatives such as the Sino-
German RECAST: Urumqi project [13].

As part of efforts to quantify the parameters of energy efficient housing design, we inspected several
solar maps of the region [1, 14], but had to conclude that they were incompatible with each other. One
map described the solar irradiation in Xinjiang as far higher than in Tibet, just to the south, while the
other map implied the opposite. Xinjiang is a very arid region with high dust levels and temperature
extremes. Tibet, on the other hand, is very mountainous and at very high altitude.

Given these factors, Xinjiang could only achieve the greater insolation of the two if its cloud fraction
is much smaller than that of Tibet. But then Xinjiang would also be recording the higher GHI values.
Unless a serious error occurred in the presentation of the results, we have to conclude that at least some
of the algorithms employed in determining the solar maps here clearly led to erroneous results in these
unfamiliar environments.

To obtain a better understanding of solar irradiation conditions, we chose four locations representative
of the region under investigation, and proceeded to collect solar irradiation details for these. These are
listed in table 1 together with site parameters.

Table 1. Selected sites in the western Peoples Republic of China.

<table>
<thead>
<tr>
<th>Site</th>
<th>Site coordinates</th>
<th>Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golmud (Geermu)</td>
<td>94°54' E, 36°25' N</td>
<td>2808 m</td>
</tr>
<tr>
<td>Kashgar (Kashi)</td>
<td>75°59' E, 39°28' N</td>
<td>1291 m</td>
</tr>
<tr>
<td>Lhasa (Lasa)</td>
<td>91°08' E, 29°40' N</td>
<td>3649 m</td>
</tr>
<tr>
<td>Urumqi (Wulumuqi)</td>
<td>87°39' E, 43°47' N</td>
<td>935 m</td>
</tr>
</tbody>
</table>

Figure 1 displays one set of irradiance maps for western China and also shows the locations of the
identified sites.

Fig. 1. Solar maps from SWERA [1] for western China.
3.2. Solar irradiation characteristics

In table 2 we collect irradiance values estimated for the four sites of study from a variety of solar irradiation maps that we were able to access. In all cases we were unable to retrieve the actual data points, and therefore estimated the irradiance on the basis of the map colour coding. These values are therefore associated with an uncertainty of ~100 MJ/m² per annum).

Table 2. Comparison of the average total annual solar irradiation data for locations in the Peoples Republic of China obtained from various resources (in MJ/m²). Data for [15, 16] are ground-based.

<table>
<thead>
<tr>
<th>Resource</th>
<th>type</th>
<th>Golmud</th>
<th>Kashgar</th>
<th>Lhasa</th>
<th>Urumqi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schillings et al [14]</td>
<td>GHI</td>
<td>~5500</td>
<td>~5100</td>
<td>~5600</td>
<td>-</td>
</tr>
<tr>
<td>SWERA [1]</td>
<td>GHI</td>
<td>~6600</td>
<td>~5900</td>
<td>~7000</td>
<td>~5900</td>
</tr>
<tr>
<td>3Tier [5]</td>
<td>GHI</td>
<td>~6200</td>
<td>~6000</td>
<td>~6600</td>
<td>~5800</td>
</tr>
<tr>
<td>Iu et al [15]</td>
<td>GHI</td>
<td>-</td>
<td>5880</td>
<td>-</td>
<td>5260</td>
</tr>
<tr>
<td>Tang et al [16]</td>
<td>GHI</td>
<td>~7000</td>
<td>~6400</td>
<td>~7100</td>
<td>~6000</td>
</tr>
<tr>
<td>Schillings et al [14]</td>
<td>DNI</td>
<td>~5100</td>
<td>~5500</td>
<td>~5000</td>
<td>-</td>
</tr>
<tr>
<td>SWERA [1]</td>
<td>DNI</td>
<td>~7500</td>
<td>~3900</td>
<td>~7600</td>
<td>~6300</td>
</tr>
<tr>
<td>Meteonorm [4]</td>
<td>DNI</td>
<td>~6300</td>
<td>~5600</td>
<td>~7600</td>
<td>~6300</td>
</tr>
</tbody>
</table>

We were able to obtain significant insights from a determination of the average cloud cover and optical depths at several Chinese locations, including Golmud and Urumqi [17]. Not unexpectedly, these indicate a much lower optical depth fraction due to aerosols at the former site compared to the latter. The mean cloud fraction according to that study is 53.4% at Golmud as opposed to 45.7% at Urumqi. These results confirm the expectation that the higher-altitude, more southerly Golmud is expected to enjoy a significantly greater DNI yield as opposed to the dustier low-altitude sites. The GHI values would however be more similar in view of the lower cloud cover in Urumqi, and this confirmed by the values in table 2.

We attempted to secure more ground-based GHI and DNI data for the region, and were able to determine that such data does indeed exist [18], but unfortunately the values quoted by these authors (e.g. 3760 W/m² and 3593 W/m² for Urumqi) are far greater than \( I_0 \) and hence clearly erroneous.

4. Case Study 2 – Southern Africa

4.1. The region

To evaluate the accuracy of the available solar maps for southern Africa, we have chosen to analyse data from the five locations listed in table 3.

The western interior of South Africa and the neighbouring countries of Namibia and Botswana are all dry and relatively cloud-free areas at considerable altitude above sea level, and thus meet the typical criteria of preferred solar energy generating sites [19]. In addition, the region is usually marked by low aerosol concentrations [11]. Maps such as those in figure 2 invariably confirm the high irradiance.
Table 3. Description of southern African locations.

<table>
<thead>
<tr>
<th>Site</th>
<th>Site coordinates</th>
<th>Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>De Aar</td>
<td>24°00' E, 30°40' S</td>
<td>1287 m</td>
</tr>
<tr>
<td>Keetmanshoop</td>
<td>18°07' E, 26°34' S</td>
<td>1066 m</td>
</tr>
<tr>
<td>Pretoria</td>
<td>28°11' E, 25°44' S</td>
<td>1330 m</td>
</tr>
<tr>
<td>Sutherland</td>
<td>20°49' E, 32°23' S</td>
<td>1759 m</td>
</tr>
<tr>
<td>Upington</td>
<td>21°10' E, 28°28' S</td>
<td>831 m</td>
</tr>
</tbody>
</table>

Fig. 2. Solar maps from the NREL database for southern Africa, also showing the locations of the five sites investigated in this work.

4.2. Solar irradiation characteristics

In southern Africa there is a large body of hourly ground-based global and diffuse irradiance measurements obtained over a period of 41 years at 11 stations managed by the South African Weather Services (SAWS). These stations included Keetmanshoop, Pretoria and Upington, and the data secured have been discussed in several studies [10, 20]. These data sets provide a unique opportunity to compare satellite data with real on-location measurements, and thereby test the accuracy of the available solar irradiance maps. Deduced GHI and DNI values for the five sites are listed in table 4.

In addition to the irradiances quoted above, the PVGIS database also provides the Linke turbidity values used for their GHI calculation. We note that the annual average \( \Lambda \)-values quoted by PVGIS for the South African sites are 3.5 for Pretoria and in the range 4.0-4.2 for the other four sites. The given average monthly \( \Lambda \) furthermore all show the same seasonal trend, peaking in summer and reaching their minimum in the middle of the year. This contradicts the well-established observation that aerosol concentrations reaching their maxima during the period August-October, and that the regional turbidity increases from the south-west to the north-east [11, 21]. It is in addition known through sunphotometry that the optical depth at Sutherland and De Aar is lower than would be reconcilable with Linke turbidities of the order of 4.
Table 4. Comparison of the average total annual solar irradiation data for southern African locations obtained from various resources (in MJ/m²). Data for [10, 20] are ground-based.

<table>
<thead>
<tr>
<th>Resource</th>
<th>type</th>
<th>De Aar</th>
<th>K/hoop</th>
<th>Pretoria</th>
<th>S/land</th>
<th>Upington</th>
</tr>
</thead>
<tbody>
<tr>
<td>DME/Eskom/CSIR [6]</td>
<td>GHI</td>
<td>~8500</td>
<td>-</td>
<td>~8200</td>
<td>~8500</td>
<td>~9000</td>
</tr>
<tr>
<td>NREL CSR [1]</td>
<td>GHI</td>
<td>7700</td>
<td>8050</td>
<td>7180</td>
<td>7170</td>
<td>7870</td>
</tr>
<tr>
<td>SolarGIS [3]</td>
<td>GHI</td>
<td>~7700</td>
<td>~8300</td>
<td>~7300</td>
<td>~7800</td>
<td>~8100</td>
</tr>
<tr>
<td>3Tier [5]</td>
<td>GHI</td>
<td>~6200</td>
<td>~6500</td>
<td>~6100</td>
<td>~6200</td>
<td>~6300</td>
</tr>
<tr>
<td>PVGIS Helioclim [2]</td>
<td>GHI</td>
<td>7650</td>
<td>8110</td>
<td>7850</td>
<td>7560</td>
<td>7800</td>
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<tr>
<td>PVGIS CMSAF [2]</td>
<td>GHI</td>
<td>7760</td>
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<td>8100</td>
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<tr>
<td>SAWS [10, 20]</td>
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<td>-</td>
<td>8770</td>
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<td>Meteonorm [4]</td>
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<td>~9000</td>
<td>~8800</td>
<td>~8800</td>
<td>~9000</td>
</tr>
<tr>
<td>SAWS [10]</td>
<td>DNI</td>
<td>-</td>
<td>12460</td>
<td>8300</td>
<td>-</td>
<td>10670</td>
</tr>
</tbody>
</table>

5. Discussion

We are of the view that the inaccurate estimation of aerosol concentrations, as well as the procedure for determining irradiation losses due to aerosols, need to be reappraised and modified. In the southern African case we found clear evidence that aerosol concentrations over the semi-desert-like western parts of the region were being systematically overestimated. While we have not tried to re-enact the PVGIS [2] calculations that resulted in the unexpectedly high Linke turbidity values, we consider it possible that the enhanced Λ-values may be due to a malfunctioning of the algorithm employed to retrieve aerosol concentrations from satellite images of arid regions.

At least one of the major models employed for solar irradiance calculations makes wide use of the Linke turbidity [22], and if this parameter is not estimated correctly then the irradiance determinations will likewise suffer in accuracy. We note in addition that the Linke turbidity is dependent on both airmass and the limits of sensitivity of a detector, making it a very tricky parameter to apply. These factors may combine to lead to entirely inappropriate irradiance estimates in conditions very different to those under which the models were verified. We note that there are places, even in western China and southern Africa, where irradiance maps describe the real conditions very well [23], but care is clearly required when using solar maps, and even limited ground-based validation remains an essential part of any high quality solar energy potential site evaluation.

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References


