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Assessing the potential of concentrating solar photovoltaic generation in Brazil with satellite-derived direct normal irradiation

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Abstract

With the declining costs of flat plate and concentrating photovoltaic (PV) systems, solar PV generation in many sunny regions in Brazil will eventually become cost competitive with conventional and centralized power generation. Detailed knowledge of the local solar radiation resource becomes critical in assisting on the choice of the technology most suited for large-scale solar electricity generation. When assessing the energy generation potential of non-concentrating, fixed flat plate versus concentrating PV, sites with high levels of direct normal irradiation (DNI) can result in cost-competitive electricity generation with the use of high concentrating photovoltaic systems (HCPV). In large countries, where the transmission and distribution infrastructure costs and associated losses typical of centralized generation must be taken into account, the distributed nature of solar radiation should be perceived as a valuable asset. In this work we assess the potential of HCPV energy generation using satellite-derived DNI data for Brazil, a large and sunny country with a continental surface of 8.5 million km^2. The methodology used in the study involved the analysis of global horizontal, latitude-tilt, and direct normal solar irradiation data resulting from the *Solar and Wind Energy Resource Assessment (SWERA) Project*, and an estimate of the resulting electricity production potential, based on a review of HCPV generators operating at other sites. The satellite-derived solar irradiation data, with 10 km × 10 km spatial resolution, were analysed over the whole country, in order to identify the regions where HCPV might present a considerable advantage over fixed plate PV on an annual energy generation basis. Our results show that there is a considerable fraction of the national territory where the direct normal solar irradiation resource is up to 20% higher than the latitude-tilt irradiation availability. Furthermore, these sites are located in the most industrially-developed region of the country, and indicate that with the declining costs of this technology, distributed multi-megawatt HCPV can be a good choice of technology for solar energy generation at these sites in the near future.

Keywords: Direct normal irradiation (DNI); High concentrating photovoltaic systems (HCPV); Grid-connected photovoltaics; Solar energy resource assessment

1. Introduction

Grid-connected solar photovoltaic (PV) generation is enjoying considerable year-on-year cost reductions, driven mostly by the production volumes resulting from the incentive programs promoted by a number of developed nations led by the German example of the feed-in tariff model. Solar electricity is expected to be cost competitive in many countries worldwide in the present decade, and a choice of technologies and technological approaches are available to select from, when considering an investment in photovoltaics. Concentrating photovoltaics (CPV) and especially high concentration photovoltaics (HCPV) presents a number of

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advantages when deployed at sites with a high level of direct normal solar irradiation.

Concentrating photovoltaics (CPV) technology has been studied since the 1970's with the construction and test of 1 kWp, low concentration (40×) non-commercial prototypes. Following this development a pre-industrial, not yet commercial, 350 kWp power plant was built and deployed in Saudi Arabia (Sala and Luque, 2007). Only in the past few years CPV has evolved from prototypes to industrial production and field deployment (Lerchenmüller et al., 2005, 2007; Perpiñan, 2008; Bett et al., 2009). The advantage of HCPV when compared with standard or flat plate PV is the substitution of large area, high cost semiconductor PV cells by less expensive lenses or mirrors, capable of concentrating sunlight on a much smaller area, high efficiency PV cell. As a consequence, it is expected that HCPV systems produced in large volumes can result in installed costs lower than the cost of traditional flat plate crystalline silicon photovoltaics for terrestrial applications (Luther et al., 2006). Lerchenmüller et al. (2005) have presented operational results for their FLATCON PV system, showing that at an installed system cost of 2.5 Euro/Wp, this technology can compete in advantage with non-concentrating flat plate PV for direct normal irradiation (DNI) levels larger than 1400 kW h/m^2/year. Furthermore, the typical HCPV system is a high stand two-axis tracking structure, sparsely distributed, which leads to a low ground cover ratio, when compared with flat plate PV without concentration, with the additional advantage that in many cases, areas around a HCPV mounting structure in a solar farm can still be used as farmland for agricultural purposes.

When assessing the potential of concentrating solar photovoltaic generation, detailed knowledge of the local solar radiation resource is even more critical than for the performance assessment of flat plate PV. At the high concentration rates involved in HCPV, time resolution as well as uncertainty in radiation data play a complex role, as demonstrated by Perpiñan et al. (2008), Burger and Rüther (2006), Vijayakumar et al. (2005), Boland and Dik (2001), Gansler et al. (1995), Aguiar and Collares-Pereira (1992), Skarveit and Olseth (1992), Suehrcke and McCormick (1988), and Collares-Pereira and Rabl (1979). For fixed, non-concentrating flat plate PV, solar irradiation resource data is commonly available, and is typically presented in the form of global horizontal irradiation data sets. For HCPV however, DNI data is not usually available, due to the cost and complexity of the instrumentation and procedures involved in gathering and treating such data.

The United Nations Environment Programme (UNEP) and the Global Environmental Facility (GEF) have supported a scientific program designed to address the issue of building up a reliable database in solar and wind energy resource (Martins et al., 2008a,b). The so-called SWERA Project (Solar and Wind Energy Resource Assessment) aimed at providing high quality information to enable and foster the uptake of renewable energies in a number of developing countries' energy mix. The SWERA Project has collected high quality information on solar and wind energy resources, compiled into consistent geographic information system (GIS) analysis tools for developing countries into three large regional groups: Africa, Latin America and Asia. The project's main target groups are government and private sector stakeholders involved in the development of the energy markets in these countries, enabling policy makers to assess the technical, economic and environmental potential of large-scale investments in renewable and sustainable energy technologies. More detailed information on the general goals and main results and products of the SWERA Project for Brazil and other countries can be found at http://swera.unep.net/.

In this work we present an assessment of the potential of concentrating solar photovoltaic generation in Brazil, making use of the extensive database of satellite-derived direct normal irradiation, at a 10 km × 10 km resolution. We compare the DNI with both global horizontal, as well as tilted plane (for tilt angles corresponding to local latitude) irradiation levels for the whole country, and develop a set of maps, which compose an atlas highlighting the potential of concentrating PV over the national territory on a monthly and annual basis. Assuming knowledge of certain basic features of HCPV systems operating in the field and described in the literature, we devise a HCPV performance map, which can be used for estimating and forecasting the energy production of HCPV systems in Brazil.

2. Direct normal irradiation and the SWERA Project in Brazil

The Centre for Weather Forecast and Climate Studies of the Brazilian Institute for Space Research (CPTEC/INPE)

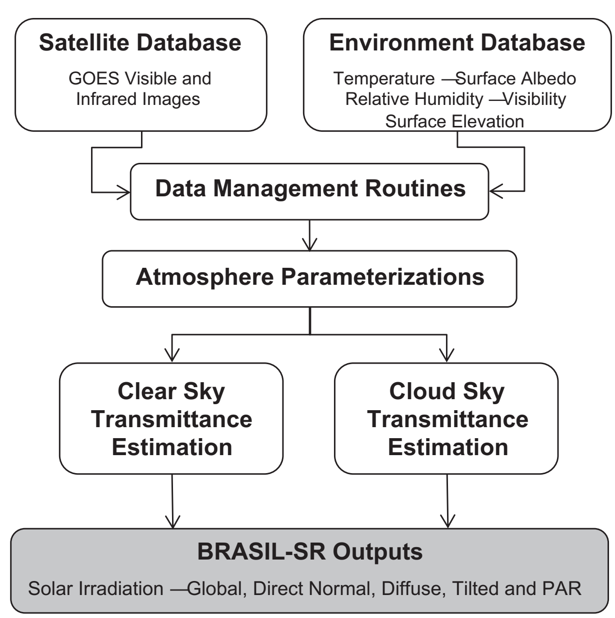

Fig. 1. Flowchart of the radiative transfer model BRASIL-SR used to derive the irradiation database used in the SWERA Project.

Table 1
Statistical deviations observed for global solar irradiation estimates provided by model BRASIL-SR for the five Brazilian geo-political regions.

Brazilian region	BIAS (W h/m^2)	BIAS (%)	Root mean square error (%)	Pearson correlation
North	353	7	15	0.85
Northeast	306	6	13	0.97
Mid-West	272	5	13	0.89
Southeast	249	5	14	0.93
South	259	5	12	0.97

Table 2
Uncertainties of the direct normal radiation estimates provided by model BRASIL-SR for SONDA network sites located at different climate regions.

SONDA site	BIAS (W h/m^2)	BIAS (%)	Root mean square error (%)	Pearson correlation
São Martinho do Serra	671	13	20	0.96
Florianópolis	504	23	29	0.95
Petrolina	565	13	18	0.96

coordinated the SWERA activities in Brazil. Together with the Solar Energy Research Laboratory at Universidade Federal de Santa Catarina (LABSOLAR/UFSC), the Brazilian Centre for Wind Energy (CBEE), the Brazilian Centre for Research in Electricity (CEPEL), the State University of New York (SUNY) and the National Renewable Energy Laboratory (NREL), the solar and wind energy resources databanks for Brazil were compiled with a variety of useful geographic and socio-economic information, such as population distribution, per capita income, railroads, rivers, roads, electricity transmission and distribution lines, industry locations, protected areas, power plants and others. The GIS database aims at providing the government and the private investor with a simple and easily available tool to identify the promising areas for wind and solar energy projects and to perform otherwise intricate queries to evaluate the risk and benefits for solar and wind energy exploitation.

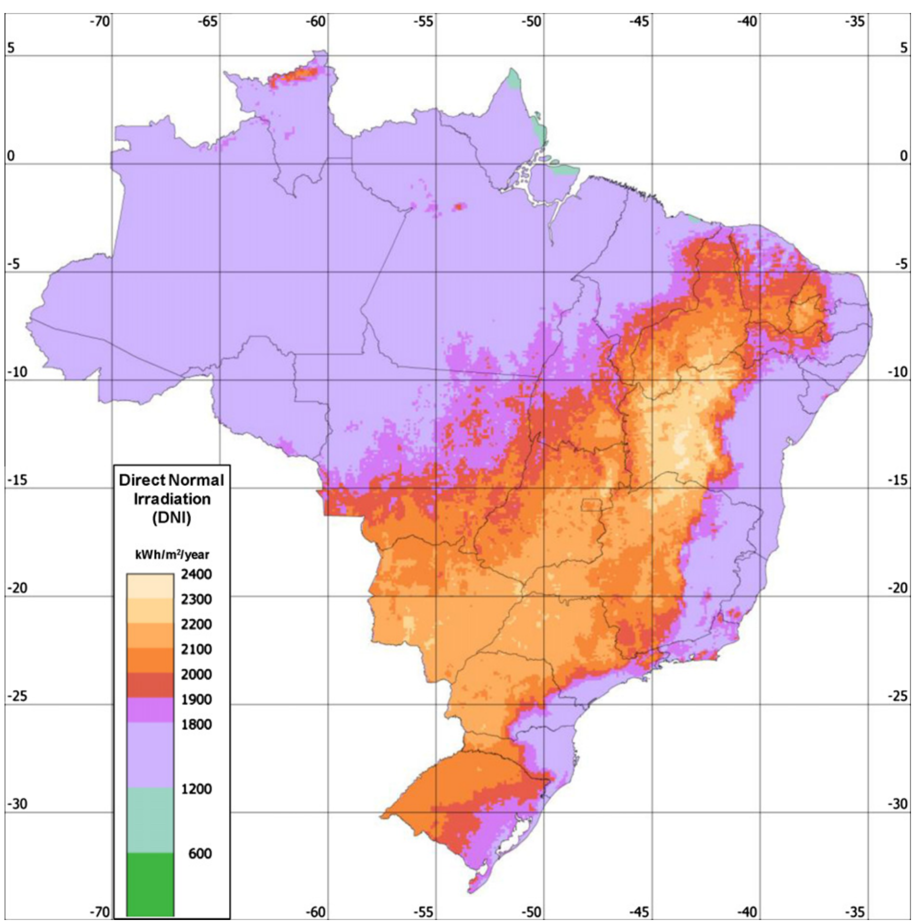

Fig. 2. Satellite-derived, total annual direct normal irradiation (DNI) map for Brazil in kW h/m^2/year.

The solar irradiation data provided by SWERA is based on the model BRASIL-SR, developed by CPTEC/INPE and LABSOLAR/UFSC (Pereira et al., 2000), which is a physical method based on a radiative transfer model described in Stuhlman et al. (1990). It uses cloud cover data acquired from geostationary satellite images, together with climate data to parameterize the radiative process in the atmosphere. The radiative transfer model BRASIL-SR was used to obtain solar flux estimates at the surface (Pereira et al., 2006). Fig. 1 shows a simplified version of the model's flowchart. The estimation procedure is divided into three steps: (i) gathering of climate and satellite data; (ii) numerical resolution of the radiative transfer equation for clear and overcast sky conditions using the "Two Stream" approach; and (iii) calculation of each solar irradiation component for any sky condition (global, direct and diffuse). The database for the first step comprises six variables: air temperature at the surface, relative humidity, atmospheric variability, surface albedo, surface elevation and effective cloud coverage. The global solar irradiation at the surface in any sky condition is obtained from a linear relation between the solar radiation flux at the surface in clear and overcast sky conditions. The cloud cover index (CCI) is the weighting factor between those extreme conditions, and the confidence and reliability of the CCI is a major factor in obtaining accurate solar estimates. A more detailed description of the model BRASIL-SR can be found elsewhere (Martins et al., 2008a,b; Pereira et al., 2006).

Direct normal irradiation was estimated assuming that the absorption by clouds is not significant and that the contribution of scattering of the solar radiation by clouds may be added to the atmospheric transmittance in clear sky conditions. The solar irradiation on a tilted plane was obtained by using the methodology developed by Perez et al. (1987).

The reliability levels of the solar irradiation estimates were performed in two steps: (i) comparison with estimates provided by the core radiation transfer models adopted by the SWERA Project to map the solar energy in other countries participating in the project; and (ii) comparison among the estimates with solar radiation flux measured at the surface (ground truth). The results obtained in the first validation task demonstrated that the model BRASIL-SR presents similar performance as any other radiative transfer model adopted in SWERA (Beyer et al., 2004). In the second task, the solar flux estimates provided by the model BRASIL-SR were compared with ground data acquired at sites spread along the Brazilian territory. The model BRASIL-SR achieved a similar performance in all geographic regions of the country, with a slight overestimation of the solar flux (averaged at 6%), and the root mean square error was about 13% over the

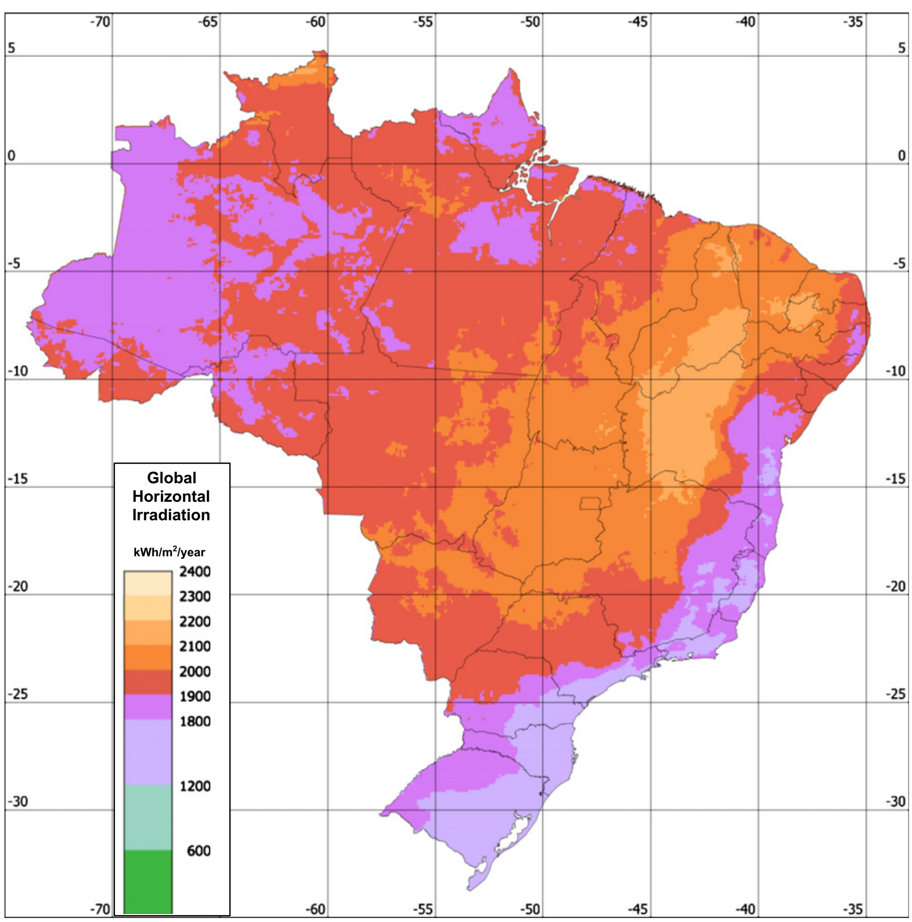

Fig. 3. Satellite-derived, total annual global horizontal irradiation map for Brazil, in kW h/m^2/year.

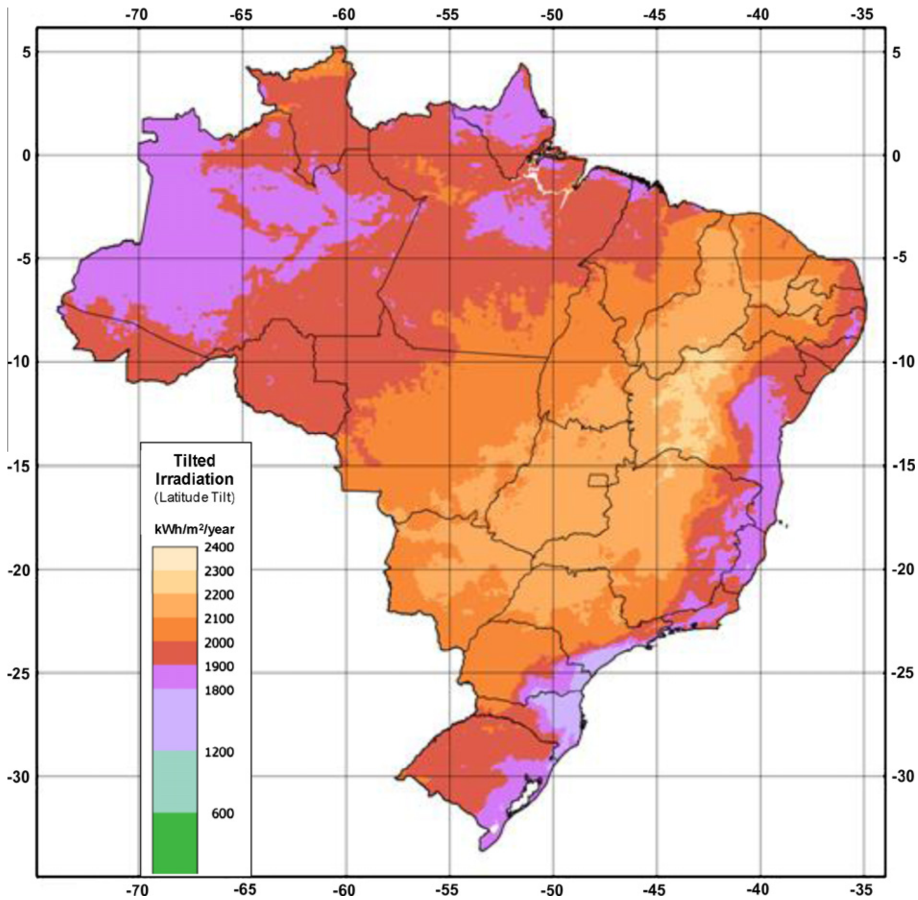

Fig. 4. Satellite-derived, total annual latitude-tilted irradiation map for Brazil, in kW h/m^2/year.

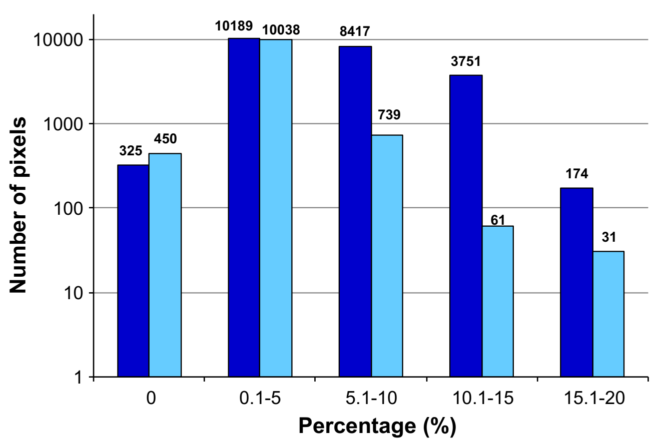

Fig. 5. Histogram with the distribution of pixels (surface area of 10 km × 10 km) for which the DNI is equal to or larger than global horizontal (left, dark bars) and latitude-tilted (right, light bars) solar irradiation.

whole territory (Martins et al., 2008a,b). Larger deviations were observed in the Amazon region, which presents a higher precipitation level over the year, and also where ground station maintenance was more complex, reducing the confidence of ground data. Gambi et al. (1998) studied the systematic deviations between incident surface solar radiation and satellite model data in 21 cities of several sizes in Brazil and found that large cities (population above 1 million inhabitants) presented a model overestimation in the range from 0.8 to 0.4 kW h/m^2. They attributed the bias to local emissions of aerosol by the several manmade sources. Pereira et al. (1999, 2000) reported that one of the major sources of aerosol loads in the Brazilian atmosphere is linked to the burning of biomass for the creation of new pasture lands and other agricultural purposes. These studies have shown that the model overestimation for clear-skies incident solar radiation during the biomass burning season in Brazil (July–November) is over five times larger than during the rest of the year. Furthermore, Martins and Pereira (2006) have implemented the parameterization of aerosol in the model BRASIL-SR in order to take this effect into account and reported an improvement in the correlation among estimates and measured values by adopting an aerosol composition with 5% of black carbon aerosols. Uncertainties of the model BRASIL-SR for global solar irradiation estimates for each of the Brazilian geo-political regions, shown in Table 1, were obtained by comparison with solar radiation data acquired at SONDA ("*Sistema de Organização Nacional de Dados Ambientais*", National Organization System for Environmental Data) network sites (http://sonda.cptec.inpe.br/) and automatic weather measurement sites (AWŚs) spread out along Brazilian territory.

The validation of the direct normal irradiation estimates used ground data collected at the SONDA network sites located in Petrolina (semi-arid region at the Brazilian Northeast region), Florianópolis (coastal area) and São Martinho da Serra (rural area at the south of Brazil). The AWS's and the other SONDA sites do not have a pirheliometer to acquire the direct normal irradiance data. Table 2 shows the deviations values and correlation factor presented by direct normal radiation estimates provided by model BRASIL-SR for those sites. The larger bias was observed at the coastal area in reason of the complexity related to the parameterization of the meteorological conditions observed in ocean/continent interface. As expected, the better results were obtained for Petrolina, located in the drier region of Brazil, with more than 250 days in clear sky conditions.

High resolution (10 km × 10 km), 10-year period (1995–2005) data resulting from the SWERA Project were compiled into solar irradiation maps, which will be presented and discussed in this paper.

3. Concentrating solar photovoltaics and direct normal irradiation in the Brazilian electricity generation context

A typical HCPV system is comprised of concentrating optics (lenses or mirrors); small-area, high-efficiency solar cells; a passive or active cooling strategy for keeping the cells at an appropriate temperature; a mechanical tracking unit that ensures that the solar cell surfaces are always facing the direct solar irradiation beam; and a DC–AC converter (inverter) for interfacing the solar generator with the electricity grid. With the accelerated development of high-efficiency silicon and multi-junction III–V compound PV cells in recent years (Luther et al., 2006), there is a renewed interest in HCPV. There are currently some 25 companies worldwide in the HCPV market using concentrating factors over 200× (Hering, 2008), and it is expected that volume production will reduce costs to a competitive level with flat plate PV.

For concentrating solar photovoltaics, the tracking accuracy of the mechanical tracking unit is a critical issue. The HCPV modules deliver maximum power with the sun irradiance perpendicular to the surface, and with increasing deviation from the principal axis of the optical system and the sun irradiation, the focus point leaves the centre of the cell, resulting in a power loss defined by the acceptance angle. Lerchenmüller et al. (2007) have measured power losses of 5% and 10% respectively, for deviation angles of 0.37° and 0.47°.

Fig. 2 presents the direct normal irradiation (DNI) annual map, with the integrated average over the year presented in kW h/m^2/year. There is a considerate portion of

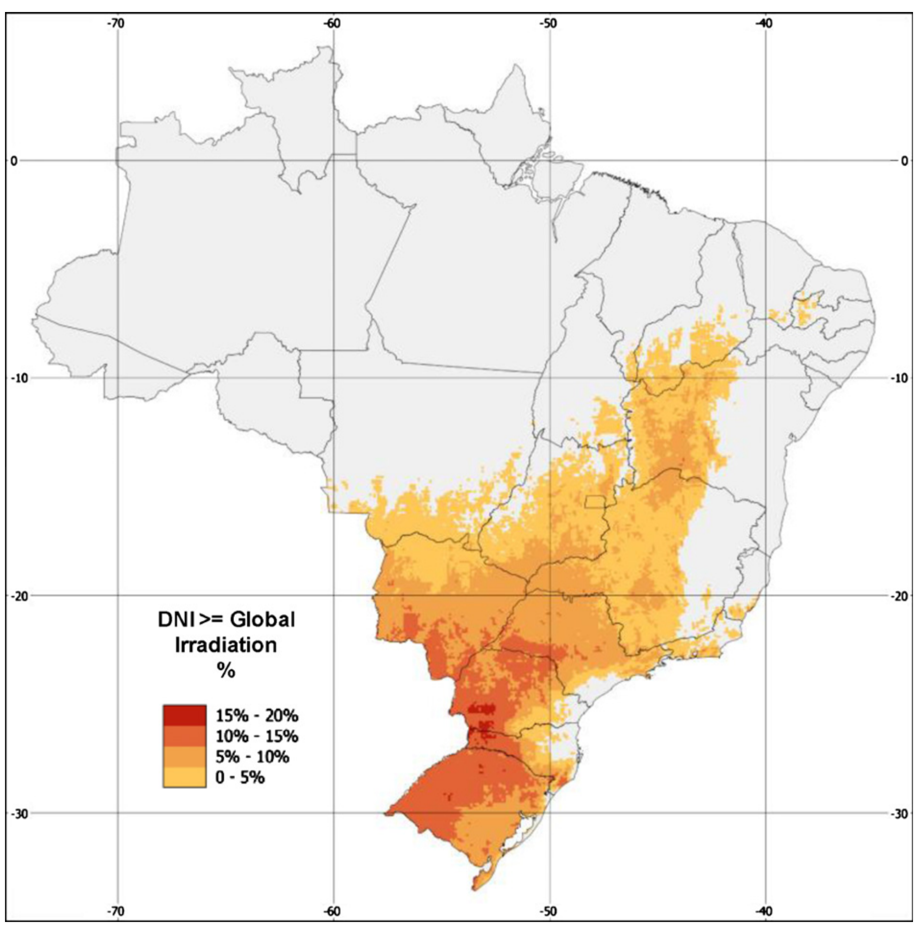

Fig. 6. Brazilian map highlighting the areas where DNI is equal to or above the global horizontal irradiation (in %).

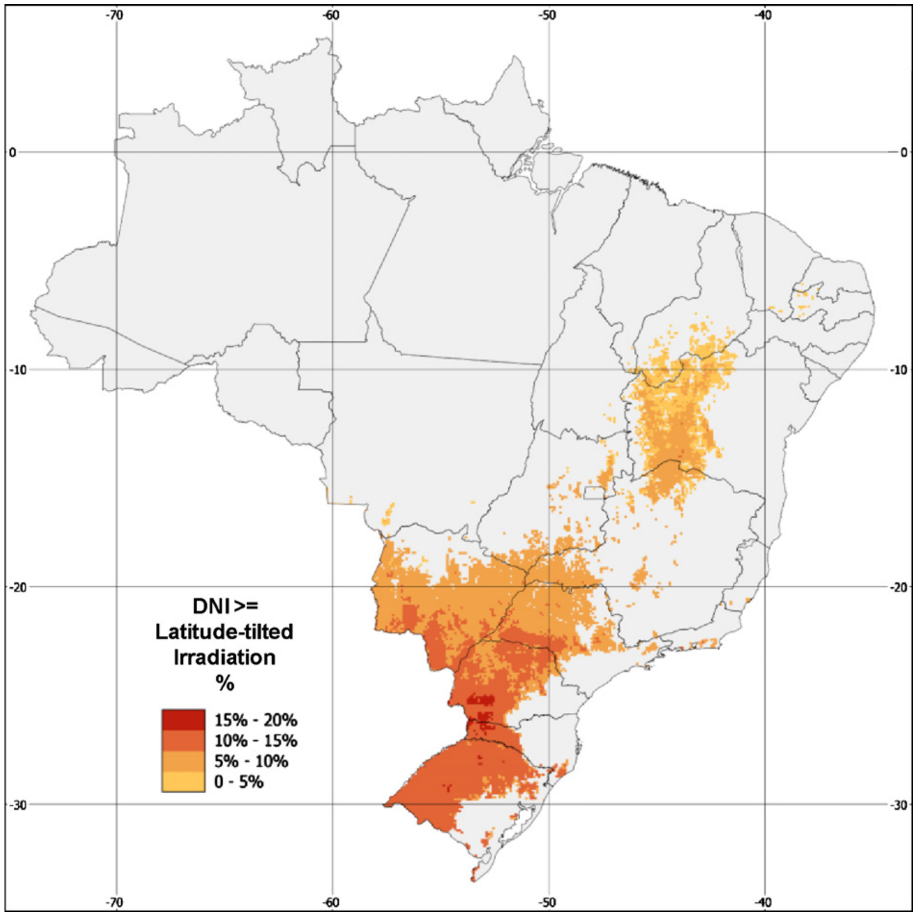

Fig. 7. Brazilian map highlighting the areas where DNI is equal to or above the latitude-tilted irradiation (in %).

the National Territory (25% of the total area), spanning from the northeast (3°S latitude) to the south (33°S latitude) of the country, and which includes some of the most industrialised areas, where DNI levels are above 2000 kW h/m^2/year. The homogeneity of the DNI levels along this extensive area is noteworthy, especially when taking into account that there are considerable climatic differences from the northeast to the south. When assessing the potential of electrical generation using HCPV, these high DNI levels should be compared with both the global horizontal, and the latitude-tilted solar irradiation levels, which are presented in Figs. 3 and 4 respectively.

In order to evaluate the potential of HCPV in comparison with non-concentrating, flat plate PV, we have analysed our database for the occurrence of pixels (corresponding to 10 km × 10 km surface area each pixel) for which DNI levels are equal to or higher than both global horizontal and latitude-tilt irradiation levels. The total number of pixels satisfying this condition also accounted for over 25% of the National Territory surface, corresponding to some 2.3 million km^2. Fig. 5 presents a histogram showing the distribution of surface area (amount of 10 km × 10 km pixels) for which the DNI is equal to or larger than the other two components of solar radiation. The percentage range bars show how much larger than the global horizontal and the latitude-tilt irradiation levels, the DNI is. Information contained in Fig. 5 led to a new interpretation of the database, resulting in a new version of the DNI atlas, highlighting the regions in the country, where DNI is equal to or larger than the global horizontal irradiation and the latitude-tilted irradiation. The corresponding maps showing these relations are presented respectively in Figs. 6 and 7. These figures reveal a somewhat surprising and relevant fact. In the southwest region, the potential for HCPV is considerably larger than expected, in comparison with global horizontal irradiation levels, and HCPV might compete in a 10–20% advantage with non-concentrating flat plate PV in terms of the available solar radiation resource. Furthermore, this region also hosts the Itaipu Hydropower Plant (14 GW installed capacity, 80–95 TW h/year energy production), the largest hydropower plant on earth in terms of total annual electricity production. The Itaipu plant is responsible for generating over 20% of all the electricity consumed in Brazil, and despite being operated as a run-of-river reservoir, it is subjected to water constraints imposed by many upstream storage reservoirs. The modular nature of HCPV makes it an ideal candidate for installation in the area adjacent to the Itaipu Power Plant, and it can in this context be considered as a serious complementary power source in the region, as hydrological and solar availability patterns are complementary. A particular and additional aspect to be considered here is the possibility of a HCPV solar park to share the 500 kV-DC transmission line especially constructed for the Itaipu plant to deliver the hydroelectricity produced in the south west border with Argentina and Paraguay, to the São Paulo metropolitan area some 900 km to the east. When compared with the results presented in Figs. 2–4, the results presented in Figs. 6 and 7 are revealing, extending the technical and economic interest in HCPV from the mostly deserted, low population northeast areas to the more energy demanding south of the country. These results are therefore not only of scientific and technological importance, but also of economic relevance as well, especially in a moment when solar photovoltaics finally starts to attract more attention in the southern hemisphere, and PV costs consistently decline.

4. Assessment of the potential of HCPV in Brazil

In this section we present a sample map of the HCPV generation atlas prepared for Brazil, showing the estimated PV generation potential on an annual basis (kW h/kW/year). The estimates for HCPV generation were based on data from field performance of systems installed in Puertollano and Seville, Spain, sites which presents very similar environmental conditions as the Brazilian regions with higher DNI levels. Estimation was also based in the quasi-linear relation between DNI and annual yield showed by HCPV systems. In sites with DNI level of 2000 kW h/m^2/year the electricity yield per installed nominal AC power (kWnom) is 1950 kW h/kWnom and for sites with level of 2500 kW h/m^2/year the yield is as high as 2475 kW h/kWnom (Gombert et al., 2009; Concentrix, 2008a,b).

The HCPV generation atlas is comprised of a set of 12 maps (Viana, 2010) with the monthly average of the estimated daily energy generation potential (kW h/kW/day), plus the annual average map presented in Fig. 8. In comparison with the PV generation atlas previously published for non-concentrating flat plate PV (Rüther, 2004), Fig. 8 shows, based on a methodology which takes into account performance levels reported in the literature for HCPV systems operating elsewhere (Lerchenmüller et al., 2005, 2007; Perpiñan et al., 2008; Viana, 2010), that an annual HCPV energy yield starting at 1400 kW h/kW/year can be expected even at the regions with the lowest DNI levels in Brazil. Under the cost figures presented by Lerchenmüller et al. (2005), these figures render HCPV cost competitive

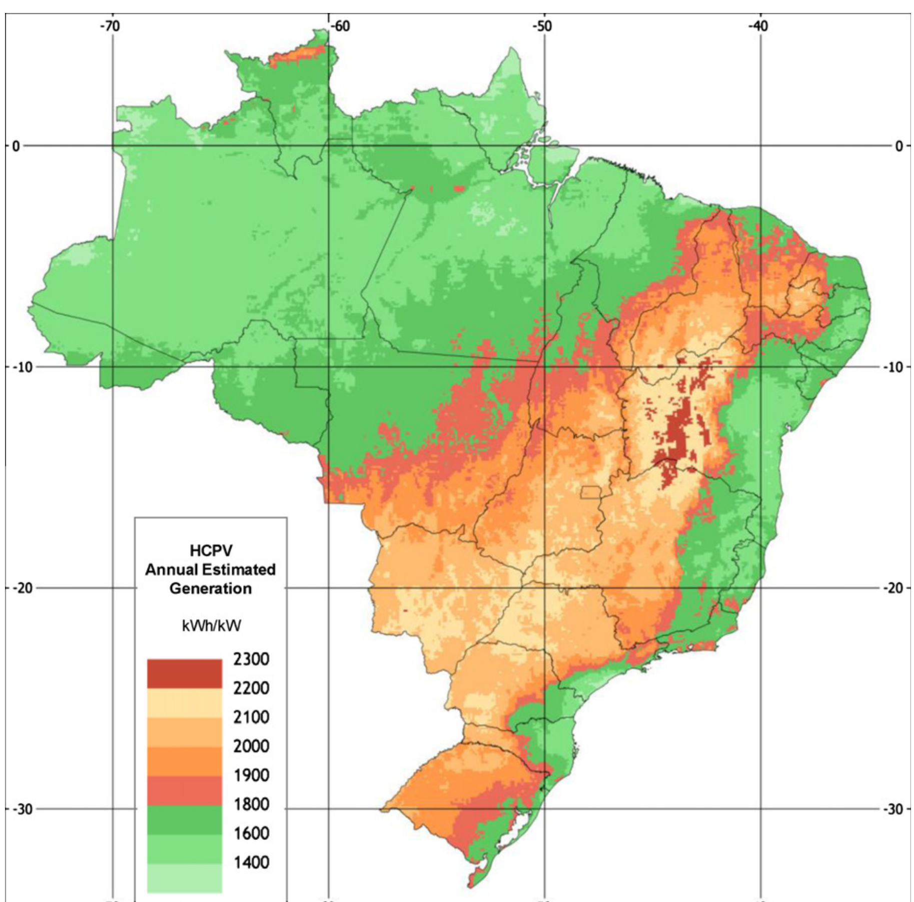

Fig. 8. Annual map of the expected HCPV electricity generation in Brazil, based on the satellite-derived DNI data and actual performance of installations operating in Spain.

for the whole of Brazil. For a considerable area of the most industrialised portion of the country, annual yields above 2000 kW h/kW/year can be expected.

5. Summary and conclusions

We have assessed the potential of high concentration solar photovoltaic generation in Brazil, based on satellite-derived direct normal solar irradiation levels. A DNI atlas, consisting of a set of 12 monthly maps, plus an annual map showing the DNI resource availability over the whole Brazilian national territory, was prepared. Based on this atlas, comparisons with global horizontal and latitude-tilted irradiation levels were presented, which revealed that in a considerable portion of the country (over 25%, corresponding to 2.3 million km^2), HCPV might be competitive with conventional, non-concentrating PV.

At current prices, only sites with DNI levels above 1800 kW h/m^2/year are believed to be appropriate for HCPV (Bett et al., 2009). However, with the declining costs of this technology, other studies have demonstrated that HCPV might be an important choice of PV technology, which might become cost competitive even at sites with DNI levels starting at 1400 kW h/m^2/year.

We have also presented a HCPV annual energy generation map, which is part of a complete atlas showing the monthly averages of the expected daily electricity generation potential for the 12 months of the year. The complete set of irradiation and HCPV generation atlases provides important information for the evaluation of potential investments in solar energy generation in Brazil. This information has revealed that the most industrialised portion of the southwest region in Brazil is also one of the most suited for the application of HCPV, with DNI levels that render this technology a serious competitor to conventional, non-concentrating, flat plate PV.

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