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Limitations in solar module azimuth and tilt angles in building integrated photovoltaics at low latitude tropical sites in Brazil

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ABSTRACT

Photovoltaic (PV) generation depends directly on the amount of radiation received by solar modules at a given temperature, and annual irradiation varies according to site location and PV array position. In this paper, the limitations and the solar irradiation levels received by building surfaces in different positions (with azimuth and tilt angle variation) in capital cities in Brazil are shown, making use of the Brazilian global horizontal solar irradiation data provided by the SWERA (Solar and Wind Energy Resource Assessment) project. These data were processed to generate figures on the irradiation at various PV module orientations and slopes for each city, which show the relative radiation levels received on specific azimuth and tilt angles in relation to the ideal position. Results were validated using four real and operating PV systems. In general, variations in azimuth or slope did not cause large annual irradiation losses up to around 20° tilt angles. This shows to PV system planners that under these fairly flexible conditions it is possible to install PV on any orientation, keeping high levels of annual irradiation, and that limitations in orientation and tilt can be relatively low. It also allows a quick analysis of PV retrofit in building-applied photovoltaics (BAPV), when seeking the best building surfaces to incorporate PV.

1. Introduction

Photovoltaic (PV) solar energy conversion has experienced a considerable and consistent growth in recent years, especially in applications connected to the public electricity grids [1]. Despite this strong increase, architects and building planners are quite often reluctant in adopting the PV technology, due to lack of training and information on the performance potential of PV modules not ideally oriented and tilted. There is a false perception among these professionals that solar modules should only be installed on ideally oriented and tilted surfaces. The development of PV modules of various technologies and in various models and sizes [2], and the possibilities to connect PV generators to the public grid [3,4] have allowed to smoothly adapt these generators to the building envelope. PV on buildings can be either building-integrated (BIPV) or building-applied (BAPV): in BIPV generators, either conventional or tailor-made PV modules become an integral part of the building envelope, replacing roofing tiles or other building elements; BAPV systems on the other hand are more typically used in retrofits, with off-the-shelf PV modules mounted on a separate metal support structure, superimposed on an existing building's roof or façade. Both BIPV and BAPV can be regarded as a potentially large market for a more widespread adoption of the PV technology [5,6], and are presently the focus of growing interest worldwide [7–12].

In order to increase the uptake of the PV technology worldwide, architects need to be informed on the potentials and limitations of integrating PV on the building envelope, since PV modules can have a considerable impact on the visual composition of buildings. A number of studies have concentrated on the architectural integration of PV in buildings [12–16], aiming at finding the best possible compromise between annual or seasonal energy generation (function) and architectural composition (form). The single most important aspect affecting the performance of PV generators is the maximisation of the incoming solar irradiation on an annual basis. The expected electricity production can be calculated based on local climatic data (solar irradiation, temperature and wind speed) or satellite-derived data [17]. Architects and builders should also be aware that shading effects can negatively affect the performance of a PV generator, and whenever a particular building surface is considered for PV integration, a specific study of the shading effects from the building envelope or surrounding obstacles on the PV generator should be carried out. Shading effects can be very specific and are outside the scope of this paper.

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Since the local annual solar irradiation levels are very much site specific, with considerable variations at a given latitude possible due to local cloud cover distribution and other climatic conditions, optimal PV module orientation and tilt angles can also be very much site specific, and the challenges for architects and PV system designers call for site specific information and calculation methods. The diffuse fraction of the solar irradiation received on a surface will also vary considerably from site to site, and will depend on the particular climatic conditions and cloud cover distribution at the site. When transposing the typically available global horizontal solar irradiation data to the plane-of-array orientation and tilt angle, a diffuse irradiation model has to be selected, which best reflects the local situation. In general terms, the largest annual irradiation levels are typically obtained when PV modules face the equator, when orientation is due North in the Southern hemisphere = azimuth 0°, and surface tilt is equal to the site latitude [12,18]. With respect to PV module tilt angles, Burger, Rüther [19] have shown that azimuthal deviations have a less relevant impact on annual PV generation at a lower latitude site (Florianópolis, Brazil = 27° S) than on a higher latitude site (Freiburg, Germany = 48° N). On the other hand, vertical façades led to lower relative energy generation losses at the higher latitude site. It was interesting to note, however, that while integrating PV on walls led to a higher loss in the relative energy production potential for the more tropical region of the globe, the absolute values were still higher than at the higher latitude site. The general notion that PV on vertical walls should be avoided at low latitudes must thus be put in perspective.

Non-ideal orientation and tilt angles can also lead to acceptable energy generation levels [20–22], but specific losses need to be assessed, and specific climatic data are needed [23]. Recent work by Beringer et al. has also shown that tilt angle limitations should be addressed more flexibly [24], as losses at latitudes close to 50° for PV systems installed at tilt angles ranging from 0° to 70° amounted to a mere 5%. At a low latitude site, we have recently shown that good compromises between form and function can be reached, where acceptable energy generation performances were obtained at an architecturally pleasant integration [25].

Compromises between the architectural composition needs (usually regarded as a higher degree of freedom in the creative aspects of architecture), and an acceptable energy generation level must be carefully analysed by building planners before defining the suitable surfaces for PV integration. If these building planners are architects, they are usually acquainted to the formal composition aspects and challenges. However, they seldom have any education or training on optimising and assessing the performance of PV generators, especially for any orientation and tilt angles deviating from the ideal, and will benefit from any possible assistance that can be made available.

In this context, this paper aims at presenting a simplified method to assist in the understanding of how PV module orientation and tilt angles affect energy generation performance at low latitude sites. Cronemberger et al. [26] and Zilles et al. [27] have presented similar studies, but our aim is to present a more comprehensive approach from the architect and building planner perspective, where compromises between form and function are relevant in the decision-making process. The paper shows a comprehensive set of diagrams that can assist PV system designers in improving their understanding about the limitations and possibilities of integrating PV on surface areas that are not ideally oriented and tilted. Real and operating PV generators were also used to validate the method. Finally, the article also presents a diffuse irradiation model analysis, indicating, for each of the Brazilian capital cities, which of the four most popular diffuse irradiation model results in the lowest deviation from satellite-derived measured data.

Recent legislation has established net metering regulations for BIPV and BAPV generators of up to 1 MWp connected to the public grid through the building electrical installation in Brazil [28]. This will stimulate the uptake of the PV technology on buildings, because in many regions of the country PV generation costs are already lower than the local utility's tariffs including taxes [29,30], without the need of any financial incentive. Architects and builders will thus benefit considerably from a straightforward method of determining the suitability of building surfaces for integrating PV generators in their projects.

Building-integrated distributed PV generation can cause frequency and voltage variations on the grid, and power quality issues should also be considered, especially where large PV generators are connected to weak utility grids. Modern PV inverters, however, can assist the grid and even improve power quality [31].

2. Method

The work described in this paper was carried out in three steps: (i) global horizontal solar irradiation data gathering for all Brazilian capital cities, and calculation of the resulting tilted plane solar irradiation for a number of different orientation and tilt angles (including assessment of best diffuse irradiation model for each site in comparison with satellite-derived data); (ii) preparation of colour contour maps for each capital city, relating the % of maximum solar irradiation availability with surface orientation and tilt angles; and (iii) validation with operating data from real PV generators.

Global horizontal solar irradiation data were originally obtained from the SWERA (Solar and Wind Energy Resource Assessment) project (http://en.openei.org/apps/SWERA/) for all 27 Brazilian capital cities. SWERA data over a 10-years period are available for all of the Brazilian National Territory at 10 × 10 km^2 spatial resolution. These data were further transposed to other orientation and tilt angles using the Radiasol software, from Universidade Federal do Rio Grande do Sul (http://www.solar.ufrgs.br/#softwares), and were finally displayed using the 2D/3D visualisation software Surfer™, from Scientific Software Group (http://www.scisoftware.com/environmental_software/product_info.php?products_id=135). This software uses worksheets to generate graphs in 2D and 3D visualisations; we used 2D maps that show the *Z* axis in different colours because it is easier to understand values than the 3D visualisation contours. The Radiasol software estimates the solar irradiation at any orientation and tilt, based on global horizontal solar irradiation data and four possible options for calculation of the diffuse component of solar irradiation, based on the Isotropic [32], Perez [33], Klucher [34], and Hay & McKay models [35] .These four diffuse irradiation models were analysed for each and all of the 27 capital cities, in order to assess which model presents the best fit with the satellite-derived SWERA data at latitude tilt in each case. More details on the method can be found elsewhere [36]. After establishing which model presented the best fit for each city, the Radiasol software was again utilised to obtain the maximum solar irradiation level possible for each site, which in some cases can be slightly off the local latitude tilt [20–22].

After defining the best possible orientation and tilt angle for each capital city, the Radiasol software was again used to estimate the solar irradiation levels at tilt angles varying from 0° to 90°, at 10° intervals, and azimuthal deviations from 0° to 360°, at 30° intervals. The Surfer™ software was then used to display all these information in colour contour maps, with the PV surface azimuth on the horizontal axis, the PV tilt angle on the vertical axis, and the corresponding irradiation levels indicated by the various colours in the contour maps as fractions (%) of the maximum possible for the corresponding city.