Case study of a model of local solar radiation potential and discussion on the associated sustainable applications and potentials

Construção de um modelo de potencial de radiação solar local e discussão das aplicações sustentáveis e potenciais associados

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ABSTRACT

The demand for a sustainable transition to energy matrices of lower environmental impact is global and current. In this sense, the modelling of solar radiation in high spatial resolution is used to assess the potential of photovoltaic generation on any type of surface and provide information for the planning and dimensioning of photovoltaic systems. From the technical potential of generation, it is possible to estimate the systems payback time and the avoided greenhouse gas emissions when adopting photovoltaic energy. In the quantitative context, the objective of this article was to briefly address the technical methodology and build a model of solar radiation of EE-IGC-UFMG buildings. In the context of sustainable applications of the tool, the objective was to address relevant topics, such as the construction of radiation models and the associated potentials, the application scales, and the difficulties and limitations of the modelling.

Keywords: GIS. Photovoltaic Energy. Model. Photogrammetry.

RESUMO

A transição sustentável para matrizes energéticas mais sustentáveis é uma demanda mundial e atual. Nesse sentido, a modelagem da radiação solar em alta resolução espacial é utilizada para avaliar o potencial de geração fotovoltaica em qualquer tipo de superfície e fornecer informações para planejamento e dimensionamento de sistemas fotovoltaicos. A partir do potencial técnico de geração, pode-se estimar o tempo de retorno do investimento do sistema fotovoltaico e a quantidade de gás carbono que deixou de ser emitido ao adotar a energia fotovoltaica. No contexto quantitativo, o objetivo deste artigo foi abordar brevemente a metodologia técnica e construir um modelo de radiação solar incidente em prédios da EE-IGC-UFMG. No contexto da discussão das aplicações sustentáveis da ferramenta, o objetivo foi tratar de temas relevantes, tais como a construção de modelos de radiação e os potenciais associados, as escalas de aplicação e dificuldades e limitações da modelagem.

Palavras-Chave: SIG. Energia Fotovoltaica. Modelo. Fotogrametria.

1 INTRODUCTION

Transforming the global energy matrix, which is mainly characterized by the use of fossil fuels, into sustainable and renewable is one of the principal ways of meeting the targets stipulated in the Paris Agreement (UN, 2015; GIELEN et al., 2016; IEA, 2018; FALKNER, 2016; ENCYCLOPAEDIA BRITANNICA Inc., 2019; HOWARD et al., 2020; MULVANEY et al., 2020; NISBET et al., 2020; TOLLIVER et al., 2020; and ZHANG et al., 2020), which aims to maintain the increase in global temperatures below the limit of 2ºC. Within this context, one of the main solutions for achieving targets in the reduction of greenhouse gas emissions is the distributed generation of photovoltaic electrical energy, given its capacity to supply electricity from a renewable source directly to users close to the capitation source in urban environments (FREITAS et al., 2015; ZINK et al., 2015; LEE, 2018; and BESSER et al., 2019).

Photovoltaic energy has a relevant influence on the changing of patterns of energy consumption and distribution in urban centers, bearing in mind that public policies for the reduction of greenhouse gases have promoted a drop in the cost of low carbon technologies.

Thus, photovoltaic energy generation systems have begun being of relevant cost-benefit, with drops in the price of modules on a scale of 10% per year being observed since 1980 (FALKNER, 2016 and FARMER and LAFOND, 2016). Moreover, in 2012, Brazil adopted Normative Resolution 482/2012 (ANEEL, 2012), regulating micro and mini-generation of electrical energy through photovoltaic generation, which, in terms of trends in Brazil, China, E.U.A and the Worldcan be observed in BP (2019) and IEA (2019), for example.

Knowing an urban center’s potential for solar electricity generation, its geospatial distribution, and the characteristics of the best sites for the deployment of photovoltaic systems could foster public policies for the development of intelligent, energy sustainable cities. As such, local governments are responsible for applying strategies that promote efficiency in solar energy production and distribution in their cities

(SANTOS et al., 2014). In order to facilitate decision-making, administrators should have detailed data on the urban infrastructure allied to geographic intelligence tools for the elaboration of models and future scenarios with robust quantitative analyses. Such decision-making should consider environmental and energy targets, besides directing public policies towards changes in legislation and investment incentives. The development of solar radiation models in a GIS environment would provide crucial information for the achievement of the aforementioned items, this being the purpose of this study.

The specific objectives of the present study are: (i) to apply a solar radiation model algorithm to the buildings of the Engineering School and the Institute of Geosciences of the Federal University of Minas Gerais (Escola de Engenharia e do Instituto de Geociências da Universidade Federal de Minas Gerais - EE-IGC-UFMG) due to the topographic differences and variability in standards and constructions of the buildings; and (ii) to discuss the following relevant aspects in regard to models of photovoltaic potential: distinct elevation models adopted as input data; the technical, economic, social, and environmental potential that the solar radiation model could explore; the practical applications for planning and decision-making; and the use of online tools and the associated difficulties.

The article is introduced by a brief summary of the theoretical basis, in which radiation models and types of DSM are discussed. Then, the methodology and results obtained in the construction of the solar radiation model for EE-IGC-UFMG are presented, whereby the greatest innovation is in the use of DRONE images. Subsequently, discussions related to the models are presented, addressing the applications and limitations of the technology.

2 MODELS AND ALGORITHMS OF INCIDENT SOLAR RADIATION

Modelling of incident solar radiation can be computed using: (i) geostatistical interpolation or extrapolation of weather station data (ASSOULINE et al., 2017; ESCOBAR et al., 2015 and Wan et al., 2015), accuracy being dependent on the density of stations – which is generally insufficient for the context of solar register; (ii) satellites coupled with thermal sensors (Melius et al., 2013), such as those of the SoDA, *European Solar Radiation Data*[1] project, and that provided by the NREL, *National Renewable Energy Laboratory*[2], which manage to cover practically the entire planet (more than 95 %). However, these are limited to an insufficient spatial resolution (they do not reach centimeter precision) and low accuracy (presenting displacements and low levels of precision); or (iii) mathematical models associated with modelling on GIS, which is the context of the present study.

The solar models based on GIS can be applied on different scales, such as in various countries, like Australia (ROBERTS et al. 2018), Sweden (LINGFORS et al., 2017), and Saudi Arabia (ASIF, 2016), in the province of Salta, in Argentina (Sarmiento et al., 2019), in the city of Berlin (KRÜGER and KOLBE, 2012), and in villages (MAVROMATIDIS et al., 2015). More recently, as a result of advances in the sphere of machine learning and processing of satellite images, it is worth mentioning solar platforms that have great potential as they are online, free, and international: *Google Sunroo*[3](recently used by MARTÍN-JIMENEZ et al, 2020) and *Mapdwell*[4] (MAPDWELL, 2018, FOX-PENNER, 2020, HEINRICH et al 2020, and LIAO, 2019).

Literature reviews approach the theme considering different application contexts, generation methods, and solar model calibration techniques. These can be consulted in greater detail in Freitas et al. (2015), Martín et al. (2015), Yang et al. (2018), Jakica (2018), and Choi et al. (2019).

The solar radiation model contemplates latitude, elevation, roof surface orientation, shade projected by the surrounding topography, seasonal variation of the trajectory of the sun, and atmospheric attenuations. Bearing in mind that not all urban infrastructure is suited to the installation of solar panel systems, due to the projection of shade from other constructions, as well as tree planting in the surrounding area (LEE, 2018), upon using DSM of the surroundings of an analyzed building it has to be possible to identify all the characteristics necessary for modelling incident solar radiation. It is also worth remembering that the more detail captured in the digital elevation model survey, the more realistic the quantification of the influence of projected shade on the reduction of photovoltaic solar energy production potential. These observations will be considered later in the article.

The GIS tools most commonly used are Solar Analyst of ArcGis and r.sun from GRASS. Both use DSM - digital matrix files with pixels that possess altitude values - and are employed in the calculation of solar irradiance on a determined surface. DSMs can be generated through Light Detection and Ranging (LiDAR) sensors, aerial photogrammetry (including the use of VANTs), or satellite images. In general, DSMs are used to compute surface elevation, inclination, and orientation, as well as shade caused by buildings, trees, or physical structures capable of blocking solar rays. Furthermore, DSMs are used in the solving of solar distance and angle equations foreseen in the models.

3 DSM FOR RADIATION MODELS IN THE GIS ENVIRONMENT

The DSMs used as input data in the solar models in GIS can be produced using remote sensing techniques with the employment of LiDAR sensors, photogrammetry, and satellite image processing. The use of satellite images to generate DSMs of sufficient resolution to be adopted in photovoltaic energy projects is recent and lacks studies, according to the knowledge of the authors of the present article. However, photogrammetry and LiDAR are consecrated technologies for the elaboration of DSMs of sufficient positional quality and sub-metric spatial resolution for the addressed context (LUDWIG and MCKINLEY, 2010; ZINK et al., 2015; and MOUDRÝ et al., 2019).

Currently, technology using LiDAR is the most adopted for urban surveys. This uses active sensors that capture the topographic surface with a much greater wealth of detail of real world elements (vegetation and construction elements, among others) through the emission ofelectromagnetic pulses with wavelengths between 10 and 250 nm (Lukac et al., 2016). The survey result consists of a point cloud, measured in points/m², which requires post-processing and classification to separate buildings, roads, structures, and vegetation. This stage is generally carried out by the service provider, who should present the adopted methodology (LINGFORS et al., 2017).

Photogrammetry is a science that has gained new dimensions with the technological popularization and advance of VANTs and computational vision algorithms, especially the Structure from Motion – MultiView Stereo (SfM-MVS) algorithm. In short, to generate DSMs and orthophotos via SfM-MVS, a photogrammetric flight should be carried out with photos sufficiently overlaid, both frontally and laterally, so that during computational processing it is possible to identify the common points in different photos. This enables three-dimensional model formation, whereby these points, containing three-dimensional information, are then used to compose a dense cloud, which is subsequently interpolated to generate the DSM and then the orthophoto (COLOMINA and MOLINA, 2014 and TONKIN and MIDGLEY, 2016). In comparison with the processing in traditional photogrammetry, the bundle adjustment stage is carried out using SfM-MVS, considering a block of images and not only one stereoscopic pair (ZINK et al., 2015).

4 CASE STUDY METHODOLOGY

4.1 CONSTRUCTION OF THE LOCAL SOLAR MODEL

The aerophotogrammetric survey was carried out at EE-IGC-UFMG, located in Belo Horizonte, MG. For an overall idea of the methodology used for construction of the solar model, Figure 1 presents a flowchart with details of each stage. The VANT used in the present study was a DJI Phantom 4 Professional (P4P).

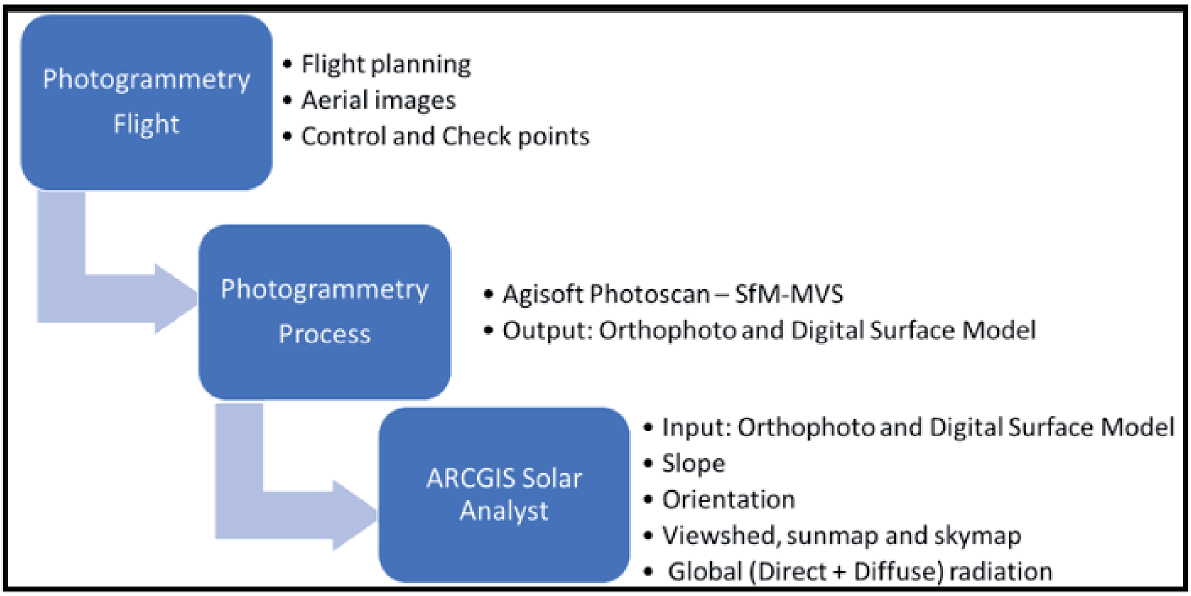

Figure 1 | General scheme of the developed methodology.

Source: Authors.

4.2 PHOTOGRAMMETRY–FLIGHT PARAMETERS AND CONTROL POINTS

The program used to plan the photogrammetry flight was the DJI Ground Station Pro (commercial program), which was also applied in research by Remondino et al. (2012) and Jakica (2018). Flight parameters, such as altitude, lateral and frontal overlays, and spatial resolution of the orthophoto and the DSM exported in .tif format are presented in Table 1.

Table 1 | Flight parameters.

Description	*Configuration*
Fkight altitude (m)	85
Sidelap (%)	75
Overlap (%)	80
Orthophoto spatial res. (cm pixel-1)	2.0
DSM spatial res.(cm pixel-1)	50.0

Source: Authors.

A GNSS CHC X91+ geodesic receptor was used for acquisition of the field coordinates of the ground control points (GCP). The present study adopted the RTK via NTRIP (Networked Transport of RTCM via Internet Protocol) positioning method, which is described with more detail in Weber et al. (2005), Dammalage et al. (2006), and Cintra et al (2011), for example.

4.3 PHOTOGRAMMETRY APPLICATION VIA AGISOFTPHOTOSCAN

Photogrammetric processing of aerial images with the final objective of constructing an orthophoto and a DSM of the surveyed area was carried out using the AgisoftPhotoscan 1.4 program. This program uses the combination of SfM-MVS algorithms to generate the cloud of three-dimensional points. In general, photogrammetry programs are considered powerful tools that are efficient, innovative, and of great impact in the field of remote sensing. For more information on the functioning of the program, articles by Colomina and Molina (2014) and Remondino et al. (2012) are recommended.

Nine control points were used, which is enough in terms of mathematical redundancy for more accurate geo-referencing of a point cloud (Figure 2), and, consequently, of the digital files arising from the same, such as the DSM and the orthophoto. The points represent a virtual 3D scene, which is invariable in relation to the scale, direction, and position of the images. The DSM was exported in controlled resolution of 50 cm/pixel for subsequent computer processing. The DSM and the orthophoto were then manipulated in the following stages using the ARCGIS 10.4 program. Vectorization of the roofs was performed manually using the same program.

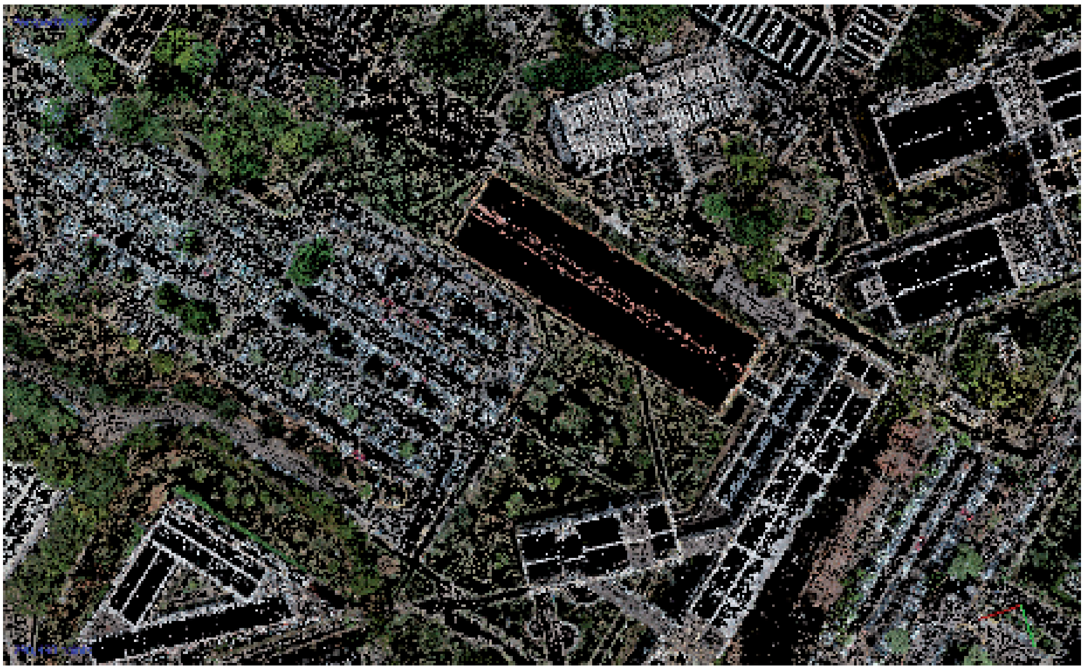

Figure 2 | Sparse point cloud.

Source: Authors.

4.4 SOLAR RADIATION MODELLING TOOL – ARCGIS SOLAR ANALYST, AVAILABLE IN THE ARCGIS 10.2 PACKAGE, OR MORE RECENT

The tool adopted in this research was the ARCGIS Solar Analyst, which first creates a set of views to the sky through calculation of the maximum horizontal angles of obstruction – caused by the topography and nearby structures. The angles are then converted into a matrix file indicating the hemispherical vision for each cell of the DSM, called viewshed.

Then, overlaying with the sunmap, showing the position of the sun over time, and the skymap is carried out; both maps (sunmap and skymap) are available in the closed package of the ArcGIS application, containing the origin sites of the diffuse radiation. In this operation, the algorithm, available on ArcGIS Solar Analyst, computes the direct radiation considering whether the sun is visible at a specific time and place, and simultaneously, the origin of the diffuse radiation. Fu and Rich (1999) addressed the processing of the Solar Analyst tool in more detail, the most recent version being that used in the present study. The obtained results were the matrix files that represent the incident radiation on the surface (KWh/m²) during the time interval, such as annual, monthly, or daily.

The main parameters of the ARCGIS Solar Analyst are latitude, skysize resolution, day and hour intervals, time configuration, slope and orientation, number of calculation directions, zenith and azimuth angle intervals, and diffusion and transmissivity coefficients (CHOW et al. 2014). For the case study in question, standard values of the algorithm were adopted, except for skysize resolution, which was improved to 512 x 512 in order to improve the shading calculation, this being sufficient and demanding more processing.

5 CASE STUDY RESULTS

5.1 DIGITAL CARTOGRAPHIC PRODUCTS (ORTHOPHOTO AND DSM)

The aerophotogrammetric survey carried out using VANT and supported by control points had an output file of an orthophoto with spatial resolution of 2 cm/pixel and a DSM of 50cm/pixel, presented in figures 3 and 4, respectively. Positional quality was verified through comparison of 9 pairs of coordinates (control points, that is, checkpoints, the general view of the location being presented in the sub-figure in the bottom right-hand corner, and the closer view, in the region of Belo Horizonte, in the sub-figure in the top right-hand corner, both without defined scale and used only for location reference, see figure 3) from the orthophoto and the DSM with those obtained from the more precise collection and processing from the GNSS geodesic receptor. With mean absolute errors less than 10 cm and standard deviations less than 13 cm, it can be verified that both possess high accuracy, which is sufficient for the objective of the present study, as per that already found by Tonkin and Midgley (2016).

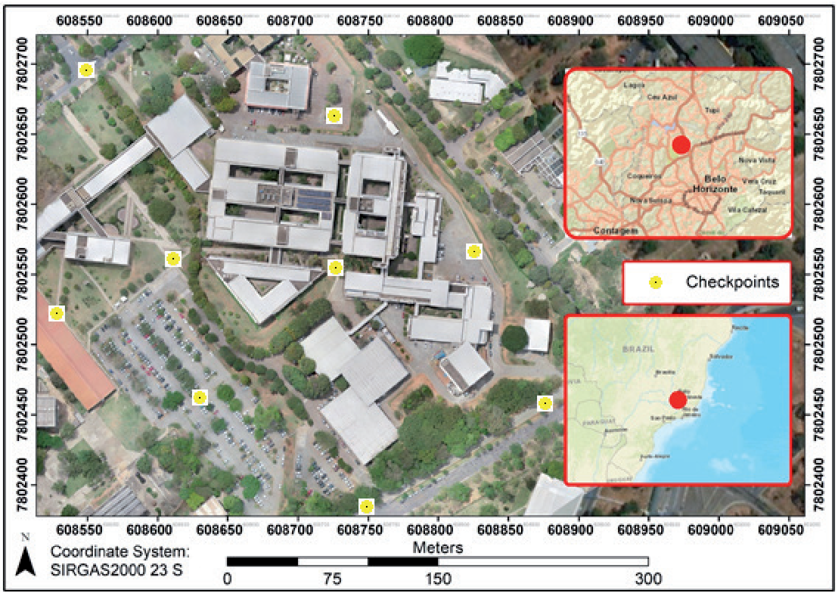

Figure 3 | Orthophoto with spatial resolution of 2 cm/pixel.

Source: Authors.

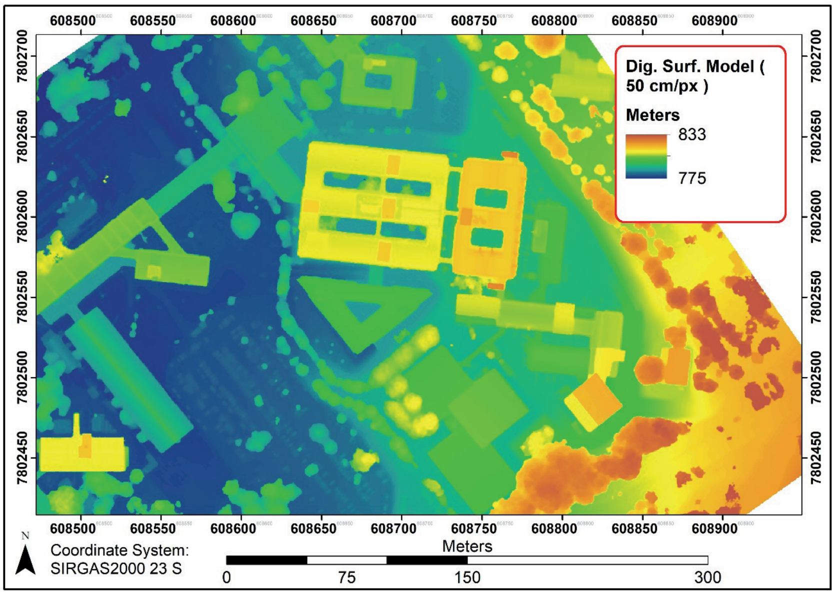

Figure 4 | Digital Surface Model with spatial resolution of 50 cm/pixel.

Source: Authors.

5.2 SOLAR RADIATION MAPS

The incident solar radiation on the surface is obtained as a result of the inclination and orientation of the same. Figures 5 and 6 present this information for the roofs of EE-IGC-UFMG. It can be noted that the roofs possess different orientations and inclinations, resulting in different results of incident radiation.

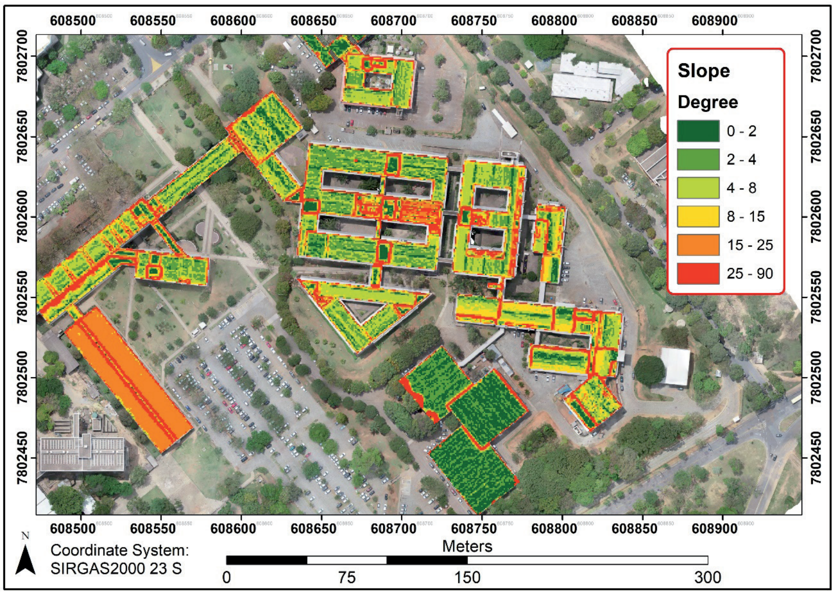

Figure 5 | Slope of the roofs of EE-IGC-UFMG.

Source: Authors.

On analyzing the radiation maps, it could be noted that some roofs have annual incident radiation of up to 1800 KWh/m², as shown in figure 7, the current demand varying and requiring better quantification. With the DSM resolution used in the computational processing of data, of 50 cm/pixel, it was possible to identify structures that impede the installation of photovoltaic systems on the roofs, thereby reducing the available area. It was also possible to observe the influence of shading caused by trees and neighboring buildings. Moreover, it can be perceived that there is greater solar incidence in the summer months in comparison with those of the winter.

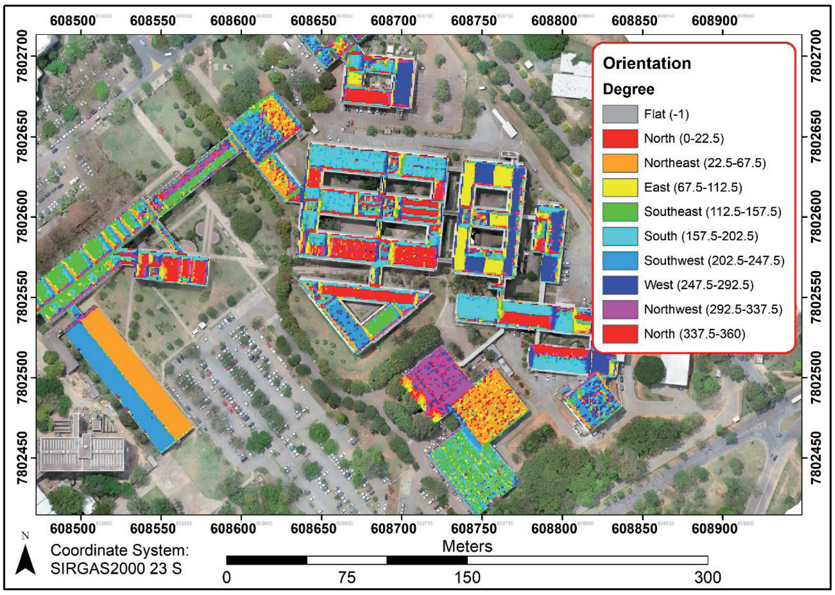

Figure 6 | Surface orientation of the roofs of EE-IGC-UFMG.

Source: Authors.

The main results of the ARCGIS Solar Analyst tool, which are the calculation of global annual and monthly radiation, are presented in figures 7 and 8.

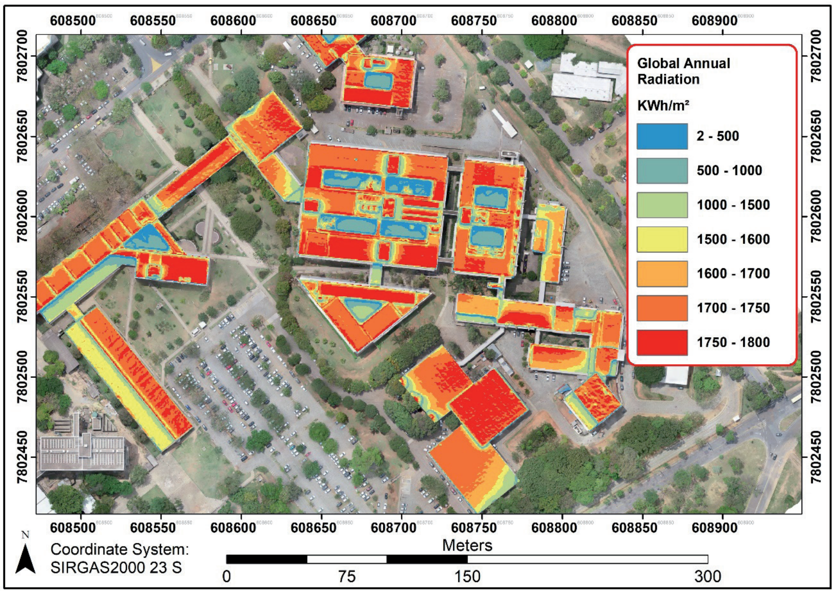

Figure7 | Global Annual Radiation of EE-IGC-UFMG.

Source: Authors.

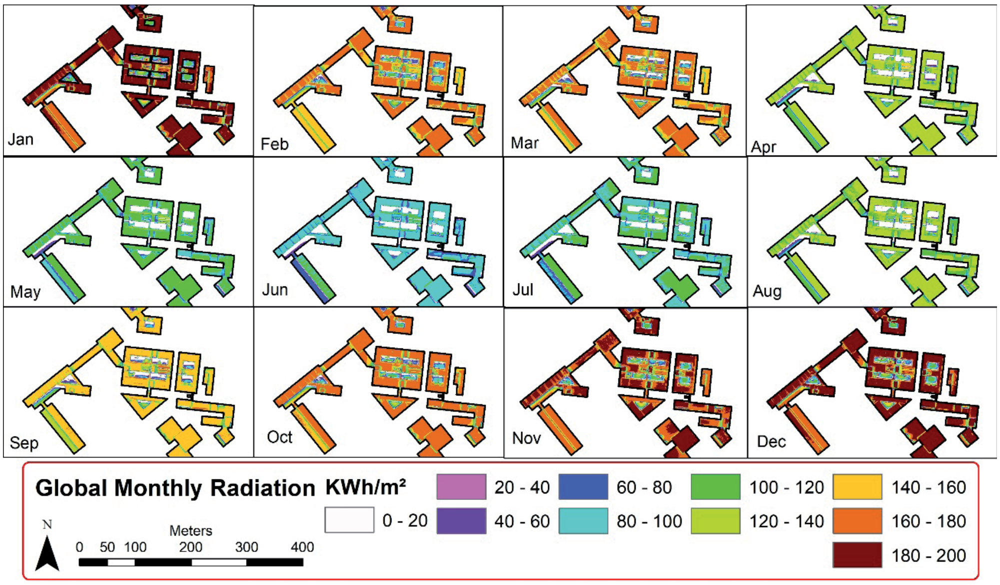

Figure 8 | Global Monthly Radiation of EE-IGC-UFMG.

Source: Authors.

6 DISCUSSION

6.1 LIDAR VS PHOTOGRAMMETRY WITH VANTS

The comparison between photogrammetry and LiDAR has already been the subject of discussion of various authors. The two technologies are viable for surveys in urban environments for the installation of photovoltaic systems. In summary, LiDAR surveys have higher relative cost per building and require greater expertise for operation and processing, and would rarely by contracted for use by a company or small city (SZABÓ et al., 2016). When it comes to large areas, greater than 1 km², photogrammetry can be used, but it also demands computational effort and expertise similar to LiDAR (TENEDÓRIO et al., 2016). It should be mentioned that for small regions, photogrammetry can generate data periodically, with spontaneity and low cost.

For the resolution of the DSM inserted into the solar modelling, it can be observed that it is mostly 1.0 m/pixel and was obtained through LiDAR. Moudrý et al. (2019) and Schuffer et al. (2015) state that DSMs with sub metric spatial resolutions are unnecessary as the variation over the year due to atmospheric conditions is significantly greater than the variation caused by different resolutions. In contrast, Besser et al. (2019) and Zink et al. (2015) indicate that on DSMs of 1.0 m/pixel it is not possible to clearly identify the area available for the deployment of photovoltaic systems, as there is no detailed representation of objects on the roofs that could impede installation, such as chimneys, elevator housings, and water tanks, among others.

Zink et al. (2015) conclude that the ideal resolution to solve this difficulty is 0.25 m/pixel and they warn that more detailed resolutions negatively interfere in the slope and orientation calculation matrix operation of the pixel, leading to false estimations of radiation. Evaluation of the sufficient resolution for identification of structures and the computational demand is recommended, which basically depends on the desired resolution and the size of the surveyed area. In the present study, 0.50 m/pixel was adopted, but more sensitive exploration of the variation in resolution is necessary.

6.2 THEORETICAL, TECHNICAL, ECONOMIC, SOCIAL, AND ENVIRONMENTAL POTENTIAL

The matrix file of the solar radiation model is expressed in KWh/m². A hierarchical methodology commonly adopted by various authors to transform theoretical potential into technical and economic potential is presented by Izquierdo et al. (2008). It consists of three stages: (i) the physical potential (theoretical), which is the solar radiation sum total; (ii) the technical potential (electrical, geographic, or urban), which reports the available area by roof and the efficiency and performance of the photovoltaic panel during the transformation of solar energy into electrical energy; (iii) the economic potential, which considers the cost of the photovoltaic system during its life cycle, which is basically the deployment and maintenance costs, local electricity prices, and the time for return on investment (ASSOULINE et al., 2017; CHENG et al., 2018; and MARTÍN et al., 2015).

The technical potential has adequate precision when the DSM has enough resolution to represent the morphologies of the buildings, the urban arrangement, and the incidental shading, as well as identifying structures on the roofs (La Gennusa et al., 2011), such as the presence of elevator housings and water tanks, among others. Another relevant detail is the correct use of algorithms for the segmentation and extraction of roofs on aerial orhighresolution satellite images, so that the measurement of the area available for deployment of photovoltaic (PV) panels on roofs is as close as possible to reality. GIS is also used for this crucial stage. The revision proposed by Crommelynck et al. (2016) discusses techniques for the vectorization of roofs in photogrammetric surveys with VANTs, while Camargo et al. (2018) used the open tool of PKTools, and Ninsawat and Hossain (2016) used eCognition software to carry out roof segmentation. It is also worth highlighting the work carried out by Faria (2017).

The efficiency and performance of the photovoltaic system will depend on the model, inverter, and time of use, as indicated by Wigiton et al. (2010) and Lukac et al. (2014). Non-linearity is a factor inherent to the semi-condutor materials that make up the photovoltaic panel and to the maximum points of inversion (LUKAC et al., 2014). Thus, the more information in respect to the efficiency of the adopted material (organic, amorphous silicon, monocrystalline or polycrystalline, etc), the greater the accuracy of the estimation of energy produced, and, consequently, the better the strategic planning will be. For example, monocrystalline and polycrystalline silicon panels have more than double the efficiency of the others cited (BERGAMASCO and ASINARI, 2011).

Other authors have considered it relevant to work with the information generated by the solar radiation model to evaluate the possible environmental impacts (IZKARA et al., 2019, DESTHIEUX et al., 2018, and NOWACKA and REMONDINO, 2018). Through the electrical-energy generation potential it is possible to obtain the quantity of CO2 that would have been emitted, if a fossil fuel had been used as a source of energy (PENG et al. 2013), also known as carbon equivalent, or CO2e. Esclapés et al. (2014) define the conversion rate as 0.60 KgCO2e / KWh produced, while Lukac et al. (2016) estimated 0.53 KgCO2e / KWh.

With this information, public administration has quantitative data to develop environmental policies combatting climate change (CAMARGO et al., 2015) and can include CO2e arising from distributed microgeneration in environmental targets. Mavromatidis et al. (2015) state that in the case of absence of environmental policies, it is common to follow economic criteria in decision-making processes.

Regarding the social dimension, two approaches proposed by Swam and Ugursal (2009) can be highlighted; top-down and bottom-up. The first consists of considering residential sectors in blocks, whereas the second consists of individually evaluating the final consumers. The scale and purpose of mapping solar radiation defines which approach to adopt. Santos et al. (2014) estimated the energy demand of each building and classified the buildings into groups based on mean local demand per capita, volumes, area and height of the buildings, and population distribution. Wigiton et al. (2010) adopted population density and roof-area demand per capita to quantify photovoltaic potential in Ontario (Canada) for public renewable energy policies. Gooding et al. (2013) established socioeconomic criteria such as income, education, environmental awareness, quantity of buildings, and owners to identify places with greater potential. In a study on microgeneration diffusion using solar tools, Kauzika et al. (2017) also indicated four social criteria of greater relevance to harnessing photovoltaic potential on buildings: income, property value, neighbors that already have photovoltaic panels, and energy consumption.

6.3 APPLICATION OF THE SOLAR RADIATION MAP

The availability of data on photovoltaic energy has been increasing, as has the number of cities making this information available. When it comes to sustainable targets, modelling the phenomenon of solar radiation on roofs is interesting to public administrators and investors looking to integrate urban planning and microgeneration (Fonseca et al., 2015).

Therefore, town planners and public administrators require a comprehensive vision of the opportunities and the cost-benefit to optimize energy performance of the buildings. They also have the responsibility to reveal and effectively communicate to the population the information on photovoltaic and economic potential, in order to maintain the population informed and shorten the energy transition at the site. Notably, solar models on GIS are tools that should be exploited to meet these demands. Castellanos, et al. (2017) maintain that having precise, accessible tools of easy understanding to evaluate photovoltaic potential is expected for the development of suitable public policies. They also warn that policy decisions are difficult, as administrators depend on generic information from low-resolution solar models, or they need to invest high amounts in researching a certain area in high resolution.

According to Santos et al. (2014), basic planning for investment in photovoltaic systems should contain information in relation to energy demand and generation capacity. Furthermore, adopting a bottom-up approach, of building discretization, is essential to whole scale planning. For this, it is necessary to model the urban environment, incident solar radiation, and the areas available on the roofs. In general, public interest is in increasing the participation of microgeneration and private interest is in deploying photovoltaic systems to generate profit (CAMARGO et al., 2015).

More recently, authors have analyzed the energy situation more deeply, considering the maximization of the participation of microgeneration in the electricity network and the minimization of investment (MAVROMATIDIS et al., 2015; CAMARGO et al., 2015; and LINGFORS et al., 2017) rather than the direct analysis of maximum potential capacity based on technical criteria. Objectively deciding the appropriate penetration percentage and having a concrete plan to achieve it is, without doubt, a contribution to shaping energy sustainability and optimizing use of space.

However, the excessive increase in the participation of microgeneration can be harmful to the entire sector, which will be discussed in the next section. It is important to present studies that quantify the total area that is suitable for the installation of photovoltaic systems, such as that of Hofierka and Kaňuk (2009), who classified 59% of the available roof area in Bardejov, Slovakia, as suitable, 39% being residences. In a study in the district of Gangnam in Seoul, South Korea, Lee et al. (2018) classified buildings into four categories, using photovoltaic potential and profitability as technical and financial criteria respectively.

In the context of a city's sustainable transition, Radzi and Droege (2013) recommend mapping renewable energy capacity and energy flows, and understanding which roofs and open spaces are available for deployment of renewable systems of conversion into electrical and thermal energy as a basis for achieving energy independence, in a structured and purposeful manner. Moreover, De Waal and Stremke (2014) recommend solar models as tools that can provide the first steps in the debate on energy transition and precede and support the creation of spatial scenarios and strategic visions. Desthieux et al. (2018) justify that the developed online tool has the main aim of promoting energy transition on a local scale in Geneva, Switzerland.

In the context of solar mapping in urban areas, there is a trend in the adoption of online tools with an easily-understood interface for vectoringroofs to compose a solar register and for presenting objective data. Besser et al. (2019) state that this approach results in more rational, effective decisions, and the population easily obtain transparent information. Freitas et al. (2015) consider that the final stage in an evaluation of photovoltaic potential is the development of an online platform. Such platforms include: Krüger and Kolbe (2012); Jakubiec and Reinhart (2013) - which resulted in the Mapdwell project; Desthieux et al.(2018); Roberts et al. (2018) – which resulted in the APVI Solar Potential Tool (SunSPoT) project; and Izkara et al. (2019).

Websites should define their target public, adapt their content to the final consumer, and avoid hiding information or losing information quality. Besser et al. (2019) list five main duties of an online platform: (i) identification of roof parts available for photovoltaic system installation and annual production capacity; (ii) definition of the size of available area (m^2), potential installation capacity (MW) and potential generation capacity (MWh), and environmental and economic indicators; (iii) visualization of colored maps of potentials and graphs related to photovoltaic generation and economy for each roof; (iv) making information available in reference to each roof, such as orientation and inclination, among others that assist in the installation and design of the photovoltaic system; and (v) generation of PDF or CSV reports.

6.4 DIFFICULTIES AND LIMITATIONS

Despite GIS solar models being considered administration tools that solve problems and clarify decisions, they still present aspects and methodologies that are being perfected and optimized. Quantification of the maximum penetration of photovoltaic energy into the electricity grid, solar model calibration, extrapolation from solar models with dubious resolution, the relatively high costs of LiDAR surveys, and the lack of efficient communication with the target public can all be cited as examples.

One of the greatest difficulties the photovoltaic sector still confronts is the imbalance between electrical energy generation and consumption through the day. The obvious solution would be to export electricity to the electricity grid, however, for cases in which there is high photovoltaic energy penetration into the grid, this excess electricity would cause instabilities in the distribution and reduce the quality of the service, besides reducing the electrical energy tariff due to the high offer (JANKO et al., 2016; and TONKOSKI et al., 2012).

In addition, in the financial analysis, the combination of temporal gaps between production and consumption and the phenomenon of high penetration lead to a reduction in investment values and an increase in the time for a return on investment, as the cost of energy is reduced with high offer during the day while in the hours of highest consumption - at night, when tariffs are higher – there is no generation of photovoltaic energy (CAMARGO et al., 2018). Camargo et al. (2018) conclude that photovoltaic energy participation in the grid of around 20% does not generate considerable impact on the distribution and reliability of the electricity grid, whereas over 40% results in a dropin quality indicators and reliability.

Also, they state that establishing targets for a specific location requires technical and economic factor analyses to define the limit of photovoltaic participation. In a similar study, but with a village as example, Mavromatidis et al. (2015) indicate 29% as the ideal participation value so that the maximum energy demand is satisfied with the inclusion of photovoltaic generation, without the necessity to store energy. However, 58% would be the ideal participation, if there were storage, meaning that all the energy demand would be supplied by photovoltaic energy.

Regarding model calibration, Szewczyk (2018) presents calibration of cloud presence in the GRASS r.sun model and warns that in relation to the solar register, the two biggest difficulties are obtaining three-dimensional data of the urban area and the insertion of information in respect to nebulosity over the year. This was the case of Roberts et al. (2018), who used ARCGIS Solar Analyst and data from NREL for calibration, while Szewczyk (2018) adjusted the GRASS r.sun model using data from the SoDa project and pointed out that the algorithm is precise for days with clear sky, even without adjustment. Adjusting the GIS models using ground data or data from satellites with thermal sensors is extremely relevant for energy, financial, environmental, and policy planning to be developed based on real values, avoiding excesses or losses in private projects or larger scale projects.

It is worth mentioning a comparative study carried out by Castellanos et al. (2017), in which solar models based on LiDAR found in reviewed literature are compared with solar models based on satellite data, and therefore of lower resolution, such as Google Sunroof, Mapdwell, and that of the International Energy Agency. The principal results indicate variations of up to 207% between low resolution models and 115% between models of different resolutions. They also computed the percent error, accounting for differences greater than 300%. Therefore, the decision-makers are found in a difficult position, as they are dependent on low accuracy information, or will have to invest in LiDAR research, which is recognized for its high cost (CASTELLANOS et al., 2017).

Another barrier that has been discussed by authors is the functionality of the tool in the face of practicality and acceptance and participation of the target public. Jakica (2018), after reviewing hundreds of solar models, highlights the low quality in the dynamic visualization of information and criticizes the low availability of open-source algorithms. Wijeratne et al. (2018) reviewed 27 programs and applications of solar system design and management and indicated 14 problems related to the tools. It is worth highlighting: (i) the lack of meteorological data with low time intervals between the samples, high-quality 3D modelling, and roof individualization; (ii) the lack of local data on products and services related to the photovoltaic sector; (iii) the lack of information in relation to tariffs and financial analysis; (iv) the lack of information in relation to government incentives; and (v) program and application interfaces not being user friendly.

7 CONCLUSION

This article achieved its aims of constructing a solar radiation model for the buildings of EE-IGC-UFMG and discussing relevant aspects in respect to models of photovoltaic potential, such as the distinct elevation models adopted as input data; the technical, economic, social, and environmental potential that solar radiation modelling can explore; the practical applications for planning and decision-making; and use of online tools and certain associated difficulties.

It is suggested that this type of study, which is mostly based on geographical aspects of the region, is added to multi-criteria analyses that consider CO2 emission reduction targets, the cost of the tariff and the forms of financing, capacity of the electrical energy distribution system, and the energy demand, forming a robust data set for decision-making by private and public sector administrators. It should be emphasized that estimating the photovoltaic potential on buildings supports financial, energy, and environmental planning to meet social demands on a local scale.

For future research, the authors of this article plan to expand the application of solar models to the entire UFMG campus or to a small city, besides investigating further the applications and potentials addressed throughout the text.

NOTES

1 | European Solar Radiation Data: http://www.soda-is.com

2 | National Renewable Energy Laboratory: https://maps.nrel.gov/nsrdb-viewer

3 | Google Sunroof: https://www.google.com/get/sunroof

4 | Mapdwell: https://www.mapdwell.com/en/solar

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