EXTENDED ABSTRACT

Simulation and experimental calibration of solar potential on buildings – application to a case study

Filipa Rosário Dias

1. Introduction

The socio-economic and environmental consequences of climate change are one of the greatest challenges facing by the world today. They are usually associated with the current dependence on non-renewable sources of energy, namely fossil fuels, which are one of the main contributing factors for most of the Greenhouse Gas (GHG) emissions. Buildings are currently responsible for about 40% of the total energy consumption of the European Union (EU) and for 36% of its carbon dioxide (CO_2) emissions [1]. The EU has proposed a number of targets to be reached in the area of climate change and energy, and the construction industry has become one of the most crucial industries to consider in order to reach the 20/20/20 targets set by the EU until the end of 2020 [2]. In the long term, the European Commission (EC) hopes to tackle climate change and reach climate neutrality by 2050, by stimulating the energy transition of the construction sector and promoting the Nearly Zero Energy Buildings (NZEB) design [2].

During the last decades, solar energy has become one of the main alternatives to fossil fuels as a source of energy in buildings from the generation of electric energy, to water heating and heating and cooling of buildings and. The evaluation of the solar energy potential in the urban environment has thus become an emerging necessity to promote a reduction on the consumption of primary energies, as well as on the emissions of GHG. In this context, the building industry has been conducting research into more energy-efficient and cost-effective solutions to meet the energy needs of residential and/or commercial buildings. Portugal is one of the countries in Europe with the largest amount of solar radiation availability due to its geographic location (nearly 1750KWh/m^2 of global solar radiation on 2019 [3]) and thus with great potential for harnessing solar energy.

This study aims to assess the solar potential of buildings in a urban context. On a first step, an experimental campaign was performed, consisting in the measurement of irradiation values on different surfaces of Vila Luz building's envelope, a working class housing in Lisbon. These experimental results were then used to calibrate a simulation model coupling 3D-GIS (CityEngine) and Building Energy Simulation (EnergyPlus) to obtain the solar potential of the buildings based on the actual characteristics of the buildings case study and urban environment. After calibration, the yearly solar potential on the different existing elements of the case study was analysed, in particular on the façades, roofs and glazed areas.

2. State of the Art

2.1. Solar technologies

The solar optimization process is made of two stages: i) maximize the amount of solar radiation captured in the main surfaces; and ii) maximize the useful energy by converting it into natural lighting, heating (thermal solar collectors), electricity (photovoltaic - PV) or both heating and electricity (photovoltaic thermal collectors - PVT) [4]. The use of solar energy technologies, such as the thermal solar collectors and the PV, is often employed at the rooftop of the buildings. The implementation of these solutions is quite common, since they are practical solutions and very easily integrated on any kind of roof [5]. However, the main point of interest is increasingly shifting to the implementation of such technologies to building envelope elements, since it brings together the energy production with its own applications: i) thermal isolation; ii) waterproofing; iii) luminosity control (for instance, semi-transparent photovoltaic modules on the windows); and iv) structural resistance [6]. These technologies are known as Building Integrated Photovoltaic (BIPV), Building Integrated Photovoltaic Thermal (BIPVT) and Building Integrated Solar Thermal (BIST). The integration of solar systems on the outer layer of the building is considered a valuable architectural solution, contributing to the building performance with almost zero energy needs, through the production and usage of direct energy. However, these systems still pose a great challenge to the projection of a building, from an architectural and operating viewpoint [7].

2.2. Previous studies

The study on solar potential of buildings has been gaining an even more important role, especially when applied to real urban environments, since it allows the study on the influence that the urban environment has on the solar radiation received (irradiation) on a given surface (roofs, façades, glazed areas). In this sense, several studies were made considering the urban environment on which they take part [8, 9, 10, 11, 12, 13, 14]. In order to do so, multiple parameters were analyzed, including: i) local/urban scale; ii) urban density [9, 10, 11]; iii) architectural detail [8, 12, 14]; iv) level of surface discretization [9, 10, 13]; and v) properties of the materials [9, 10, 11, 12]. Despite it is importance, seldom studies focused on the validation of simulation of simulation models of solar potential on urban environment with experimental results [13, 14].

In respect to the local/ urban scale and grid density, several studies have been conducted [8, 9, 10, 11]. Catita et al. [8] made a study of an urban grid of the city of Lisbon where the building with the most solar potential, on both the roof and façade level, was identified. Heidarinejad et al. [9] considered six levels of urban density and concluded that for lower values of urban density the presence of neighbouring buildings has no influence. However, for higher values, the partial shadowing effect on the building surfaces was notorious. In the same study, [9] it was concluded that for a height of the surrounding buildings twice as high as the reference building, along with a high urban density, the irradiation values appeared significantly lower when compared with buildings of similar height (during the summer solstice and the equinox). Peronato et al. [10], also concluded that the urban density impacted the results. Additionally, for a high urban density of tall buildings, and for an erratic fluctuation of buildings height, the city tends to have a higher solar capacity [11]. Apart from the urban density, the level of detail defined in a model presents a crucial detail on the precision of the obtained results, thus meaning that it should be carefully established [8, 12].

Another important factor on the creation of a model is its level of discretization, and thus many studies were conducted bearing this value in mind, with special relevance for the study of Machete et al. [12], where elements of 3x3m^2 were considered; also the study of Catita et al. [8], where the façade and roof of buildings were analyzed through hyperpoints spaced one meter apart; and the one of Brito et al. [13], whose model detailed three distinct analysis: i) whole building, ii) surface; and iii) hyperpoints. According to [9, 10] the higher the level of discretization the more refined is the result, especially when the angle of the sun is low and the urban density is high. Additionally, the sensitivity of the façades is higher in relation to the chosen grid resolution when compared to the roofs [10].

Of equal importance in the analysis of the solar potential is the definition of the optical properties of the materials, which allows for a more realistic evaluation of the solar potential on the buildings for considering natural phenomena that occurs in urban neighbourhoods where the sun rays emitted by the sun and reflected on the surfaces interact between themselves [9]. Machete et al. [12], concluded that the characteristics of the materials in the calculation of the reflected solar radiation is only preponderant when the encasing materials of the surrounding buildings have extremely reflective characteristics, as it happens when buildings are made of exclusively glazed or metal materials.

The experimental validation allows the comparison of experimental results with simulated results to progressively bring the models closer to reality. Shiota et al. [14] compared the solar radiation for a single coverage point on clear sky day, while Brito et al. [13] compared simulated and experimental values for a summer and winter month on a single point of the façade, concluding that the largest errors were observed during the winter month due to the need of a more detailed renderization of the shadows. Hence, the emerging need to develop studies that compare values registered in-situ with numerical simulated ones is of upmost interest for the scientific community, in order to contribute for improving of the simulating models, and thus ensuring a greater closeness to reality.

With the aim of contributing to increasing knowledge in this field, the present study will draw a comparison of *in-situ* experimental and numerical values of irradiation on buildings on urban environment, more specifically on the façade of three buildings and on the courtyard area from a working class housing – Vila Luz - in Lisbon, Portugal.

3. Methodology

The methodology followed in the study consists of the following steps: i) conduct an experimental campaign for in situ irradiation measurement on building facades and courtyard surface for different periods of the year (equinox, summer solstice and winter solstice) and of the day (9:00, 12:00 and 15:00); ii) develop a 3D-GIS model of the case study urban area; iii) simulate the solar potential on buildings using a building energy simulation program (EnergyPlus) coupled with the 3D-GIS model (CityEngine); iv) assess the impact of several simulation variables; v) calibrate the numerical model with the experimental values of irradiance registered in situ in the case study; vi) application of the calibrated simulation model to the analysis of the solar potential on glazed areas, façades and roofs for the typical meteorological year (TMY) of Lisbon, Portugal

The in-situ irradiation measurements were collected using a pyranometer device [15]. To analyse the influence of the solar radiation on the buildings surfaces over a year and during the day, three days were selected for the experimental campaign: the equinox; the summer solstice; and the winter solstice and for which day three hours were chosen, respectively 09:00 AM, 12:00 PM and 03:00 PM.

The 3D-GIS model was built using *CityEngine* (*ArcGIS)* software based on geographical data provided by the Lisbon municipality (CML), including building footprints geometry and attributes such as the area; the perimeter; the number of floors; and the type of usage (residential or commercial), street network and a Digital Elevation Model (DEM), all available in Hayford Gauss - Datum73 coordinate system. The procedure starts by the importation of DEM followed by projection of the street infrastructures, enabling the application of the CGA rules for an automatic construction of the distinct levels of detail. In the case study, four levels of detail were considered: i) outer layer of the building, generated from the extrusion of the implantation polygons in function of the height attributes of the floor and the number of floors; ii) division of the surface in panels, namely, roofs and façades; iii) definition of specific architectural details of the different buildings of the case study (windows, doors and balconies) through *SketchUp* after the construction of the 3D model in *ArcGIS*; and iv) conception of an identical rectangular panel grid of 1.20x1.00m^2 on the main façade of the buildings.

The internal geometry of the buildings was not considered since it was not relevant for the current study. The modelling of the outer layer of the buildings allowed the analysis of the roof and façades solar exposure considering the shadow projection cast from the neighbouring buildings as well. Furthermore, dividing the surfaces into smaller parts allowed a thorough analysis of the solar potential on the surface of the buildings and, consequently, on the perception of the most advantageous areas for the installation of the solar energy systems. Another relevant aspect in improvement of the results lies in the definition of the constituting materials of the surfaces since they play a crucial role in the estimation of the solar radiation. Additionally, the surrounding buildings to the area case study were modelled using simple volumetric shapes, based on their highest height (e.g., chimneys if existing).

Based on the lack of interoperability between the software's it was necessary to convert the 3D GIS model to be imported to SketchUp software where the several adjustments were made through the Euclid 9.3.0 plug-in. After that, the file was processed on EnergyPlus (EP) and, after the definition of the mandatory elements, different simulations were executed to obtain the irradiance estimation. Concerning this, the impact of the following parameters was analysed: i) outdoor climatic parameters; ii) the semantics of the object; iii) urban context; iv) the intrinsic geometry of the model itself (namely balconies); and v) solar absorptance of the surfaces.

Finally, after the calibration of the model with the experimental values of irradiance registered in situ, the yearly solar potential on glazed areas, façades and on roofs is analyzed.

4. Case study

The case study is located on Rua Pascoal de Melo 111, in Lisbon, and is known as Vila Luz. This former workers village, listed as a heritage site in CML heritage building list, was built in the beginning of the 19th century behind other buildings and it stands out for the following characteristics: entrance through an iron gate with a tiled sign identifying the name of the village; access to the village through the central axis of the lot on the open sky that connects to the courtyard; a courtyard that connects the different buildings built behind the main building which are not visible from the main road; access to the superior floors through exterior galleries built in an iron structure; and, lastly, a row of houses with only a ground and first floor.

Vila Luz consists of three buildings - Building 1, Building 2 and Building 3 - and by their connecting element - the Courtyard. The Building 1 is facing the Northeast, while Building 2 and 3 are facing the southeast. The constituting materials and the opaque encasing characteristics considered in the case study are relative to the construction solutions adopted at the time of construction of these types of villages [16].

4.1. Experimental Procedure

The experimental campaign was divided in three phases of solar radiation monitorization: equinox; summer solstice; and winter solstice. When possible, the measurements were made the closest as possible to the reference dates, being however subject to the availability of weather conditions and equipment. The measurements were made in three distinct moments throughout the day: i) at 09:00 AM, ii) at 12:00 PM and iii) at 03:00 PM. The measurements made during the afternoon were made symmetrically to the solar mid-day, thus contemplating the daily and seasonal component of the Sun, allowing, as well, the comparison among the three periods of the day. Note that the sun declination is the same during both equinoxes and, therefore, it was only necessary to measure one of them. One of the main key factors for a good performance of an experimental campaign is an appropriate preparation of the monitorization. In this sense, on a first instance, several visits to the area and photographic record of the space were made, to help the choice of location for data acquisition. **Figure 4.1** identifies the location of all the points where the irradiance values were measured.

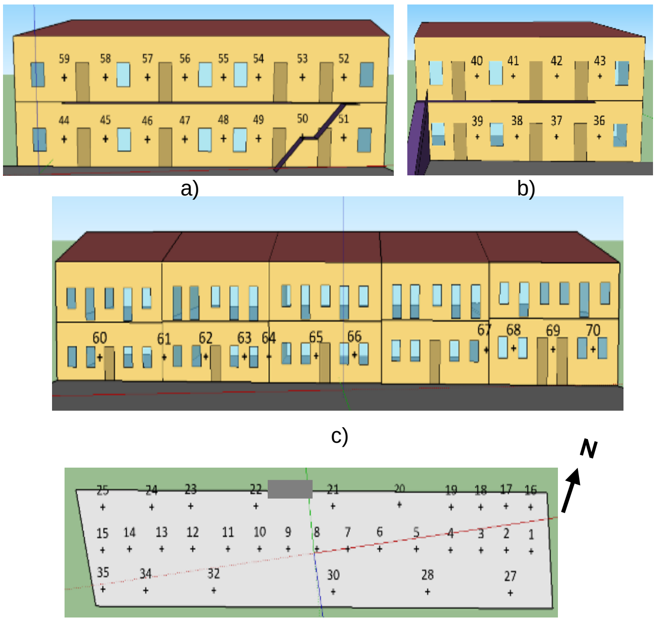


Figure 4.1 - Illustration of the location of the irradiance registration points: a) Building 3; b) Building 2; c) Building 1; and d) Courtyard

During the experimental campaign, the solar radiation was measured through a pyranometer device, vertically placed on the exterior façade of the buildings (**Figure 4.2**). On the Courtyard, the careful handling of the material was paramount, since the measurement of the solar radiation in this area was conducted 70 cm above the ground and with the sensor placed in the palm of the hand. The collection of the 66 points was executed as swiftly as possible to avoid any significant displacement of the sun between the first and the last measurement. Notwithstanding, it is important to point out that the data collection took almost one hour.

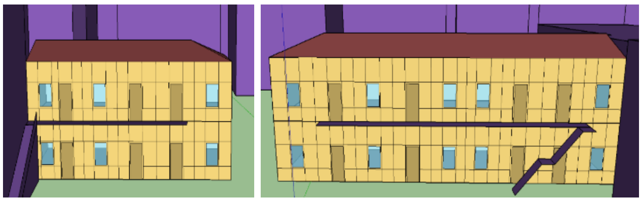
a) b)

Figure 4.2 – - Placement of the pyranometer on the vertical plane of the façade of one of the buildings: a) sensor on the wall; b) detail of the sensor on the wall.Building

4.2. 3D Geometry in SketchUp

The 3D-GIS of the village was imported to SketchUp, as it allows the link to EnergyPlus based on the Euclid plug-in. The association of these two softwares allows the creation and editing of buildings' geometry, where some geometric details were changed to accommodate the requisites of EnergyPlus.

Levels of detail modelled in SketchUp followed the following procedure: on a first instance, it was necessary to create thermal zones where the buildings and the courtyard of the village were implemented, analogously it was also necessary to create the shadowing areas where the surrounding buildings were implemented; and afterwards, the architectural elements of the village were drawn, namely the doors, windows and balconies. The first simulation considered the façades and the courtyard as a single element, not representing in an accurate way the real situation. To overcome this problem an increased level of detail was made for the base model. This way, the façades and the courtyard were divided into smaller elements (1.20x1.00m^2 surfaces), in which the centre was close to the location of the experimental campaign point. As an example, the divisions made on Buildings 2 and 3 are displayed on **Figure 4.3**, with this being the model to be adopted in the simulations of the solar potential.



a) b)

Figure 4.3 - Representation of the division of the façades: a) Building 2; and b) Building 3.

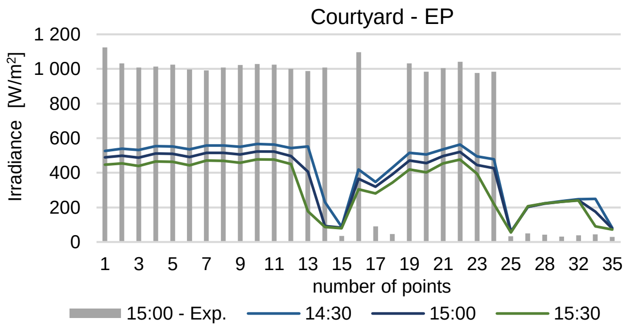
5. Results and discussion

For the calibration of the model the influence of the following parameters was analysed: i) outdoor climatic parameters; ii) the semantics of the object, which corresponds to the type of surface definition in SketchUp and in EnergyPlus, specifically: floor, roof and wall; iii) the geometry of the urban space that surrounds the case study; iv) the intrinsic geometry of the model, in particular, the presence or absence of balconies/flaps on the upper floors; v) the optical properties of the materials, namely the solar absorptance of the surfaces [16]; vi) and, lastly, the level of discretization of the model, that is, the spatial repartition in elements/panel in smaller dimensions, with the goal of obtain results as close as possible to the in-situ data.

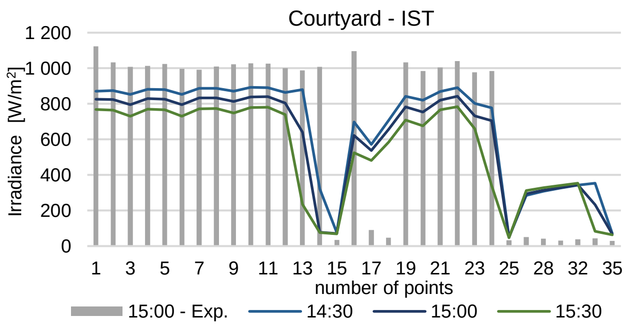
5.1. Study on the impact of the variables

5.1.1. Influence of the climate file

Simulations were made based on two distinct climate files: i) the climate file EPW made available by the website of EnergyPlus [17]; and ii) the climate file created from the data provided by the IST weather station [18]. The choice of this station owes to the fact that it is the closest one to Vila Luz, which ensures a better approximation of its real weather characteristics. The better performance was obtained by using the IST weather station, and it can be concluded that the choice of file is determinant for the quality of the results. **Figure 5.1** represents the irradiance on the courtyard for the summer solstice at 03:00 PM, where the bars correspond to the experimental values, while the lines correspond to the simulated ones.



a)



b)

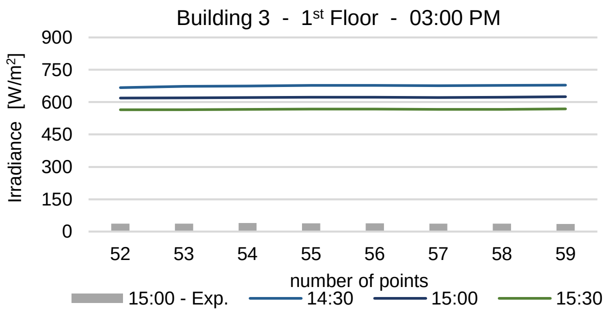
Figure 5.1 - Irradiance obtained in the courtyard at the summer solstice at 03:00pm: a) EP climatic file; b) IST climate file.

5.1.2. Influence of the semantics of the object

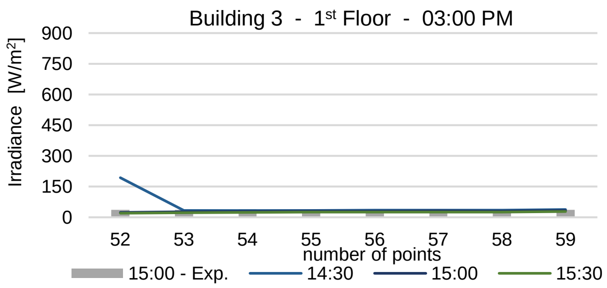
Concerning the definition of the surface of the outer court, the Euclid plug-in in SketchUp allows the semantic definition of four types of objects, namely: Floor, Roof, Wall and Ceiling. On a first analysis, the object Floor was considered for the courtyard surface which led to unrealistic results. Note that the object Floor, by default, is set for interior areas, for example, a slab of a ground floor in contact with the ground. Therefore, it must be chosen an object such as Roof or Wall, since this is the only way possible to obtain observations that correctly consider the solar radiation on the outside. It was finally opted for the object type Roof, since as it is a horizontal surface it would be the best option to consider.

5.1.3. Influence on the urban context.

A simulation was made considering: i) the Vila Luz in a standalone form - that is, only the base model and vertical elements that circumscribe the courtyard; and ii) the Vila Luz inserted in the urban environment that surrounds it. The biggest difference between the two simulations was obtained at 03:00 PM during the winter solstice. **Figure 5. 2** shows the difference between the experimental values and the numerical values, when the village is analysed on its own. The major impact it is during the winter solstice, when the Sun is the lowest and the neighbouring buildings cast a bigger shadow on the first floor. However, for the simulations made for the summer solstice and equinox, the urban environment played no impact on the results obtained. This owes to the fact that the sun is at a higher position in the sky when compared to the winter solstice. Therefore, it can be concluded that it is important to define the real geometry of the building and its surroundings.



a)

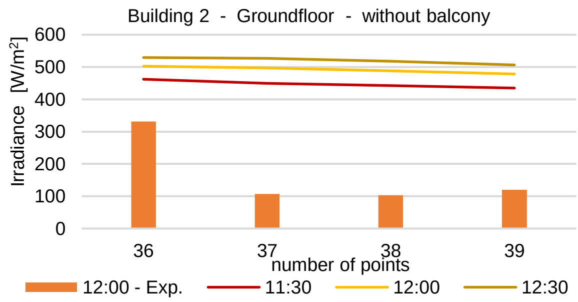


b)

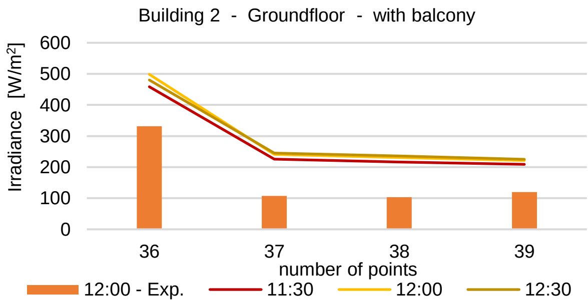
Figure 5.1 - Irradiance obtained on the façade of Building 3 (1st floor) at the winter solstice at 3:00 pm: a) Isolated Vila Luz; b) Vila Luz inserted in the urban context

5.1.1. Influence of the intrinsic geometry of the model itself

The definition of the level of detail of the model may influence the results, and to understand its impact the inclusion of the balconies on Building 2 and 3 was considered. To do so, it was analysed the summer solstice, since this is the phase of the year with the largest shadowing on the façades caused by the balconies. As an example, **Figure 5.3** shows the results obtained in the simulation comparing them to the results registered *in-situ* considering the presence and the absence of the balcony on the ground floor of Building 2 at 12:00 PM. It was concluded that the presence of the balcony is determinant on the amount of solar radiation that is received by a building and thus the importance and relevance of defining a detailed geometry in a model.



a)



b)

Figure 5.2 - Irradiance values obtained in Building 2 at the summer solstice for 12:00: a) with a balcony; b) without balcony.

5.1.2. Influence of the solar absorptance on the surfaces

The solar absorptance of the surfaces plays a fundamental role in determining the received solar radiation on a given surface. The value of solar radiation received and reflected, on the different surfaces of the case study, were measured on three stages of the campaign. Therefore, two simulations were compared: the first one considers standard solar absorptance values in the literature, while the second one considers the values measured on the different surfaces, namely on the wall and the pavement of the courtyard, with a pyranometer (**Table 5.1**). **Figure 5.4** presents a comparison between two simulations on Building 1 at 12:00 PM, considering the equinox day.

Therefore, it was concluded that by using the solar absorptance measured locally instead of the recommended value in the literature, the results obtained in Building 1 are more favourable, since they present a better approximation to the experimental results.

Table 5.1 – Values of solar absorptance

	Courtyard	Wall	Door
Solar absorptance (literature)	0,40	0,40	0,50
Solar absorptance (values measured)	0,76	0,53	0,75

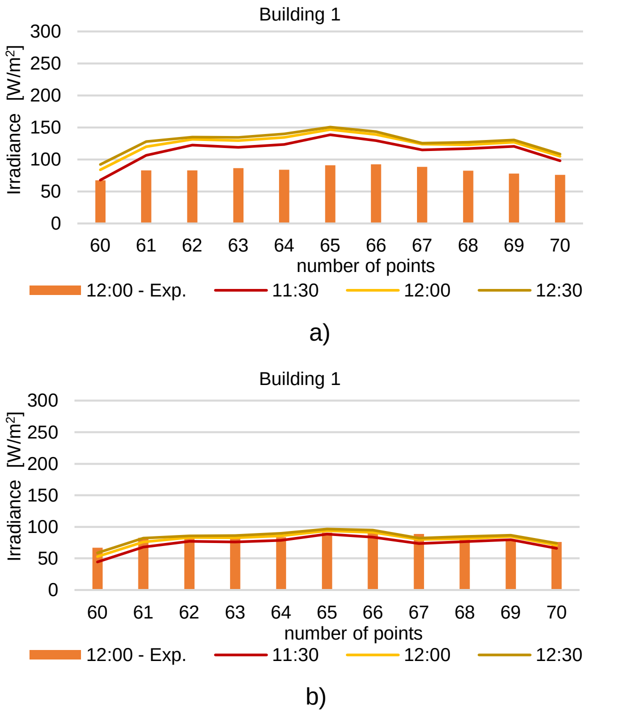


Figure 5.3 - Irradiance values obtained at the equinox by 12:00 PM in Building 1: a) solar absorptance with standard values; b) solar absorptance measured on site

5.2. Final assessment

After the detailed analysis on the impact of the variables, the following parameters were set to all geometric model: i) climate file from Instituto Superior Técnico (IST) [18]; detailed geometry of the Vila's buildings (namely, balconies); iii) Vila defined as being within the urban context; iv) material's solar absorptance as measured in the spot.

Starting with the analysis of the results from the three courtyard simulations, we can see that the values constantly diverge from the experimental values [16]. These divergences may be due to the following factors: i) irradiance measurement at 70 cm above the ground; ii) the radiance reflected from the sidewalk not being considered in the calculation of irradiance for the surfaces of the courtyard; iii) the courtyard being a place where the residents may park their vehicles which are very reflective of the solar radiance and, therefore, may lead to the increase of the values collected; iv) errors related to the human factor; v) the location of the simulation model's points being an approximation to the real coordinates of each point.

As an example, only the graphs with the simulated values and the experimental values for Building 2 at 12:00 PM, for each phase of the year, will be presented (**Figure 5.5**). The other graphs may be consulted in the original document [16].

Relatively to the equinox, at the ground floor, we can verify a great disparity of the numeric values as opposed to the experimental ones because, at this time of the year, the sun sets itself at an intermediate height along with the fact that the façades present surfaces with a relatively large size (1,20x1,00m^2), so the level of detail might not be enough.

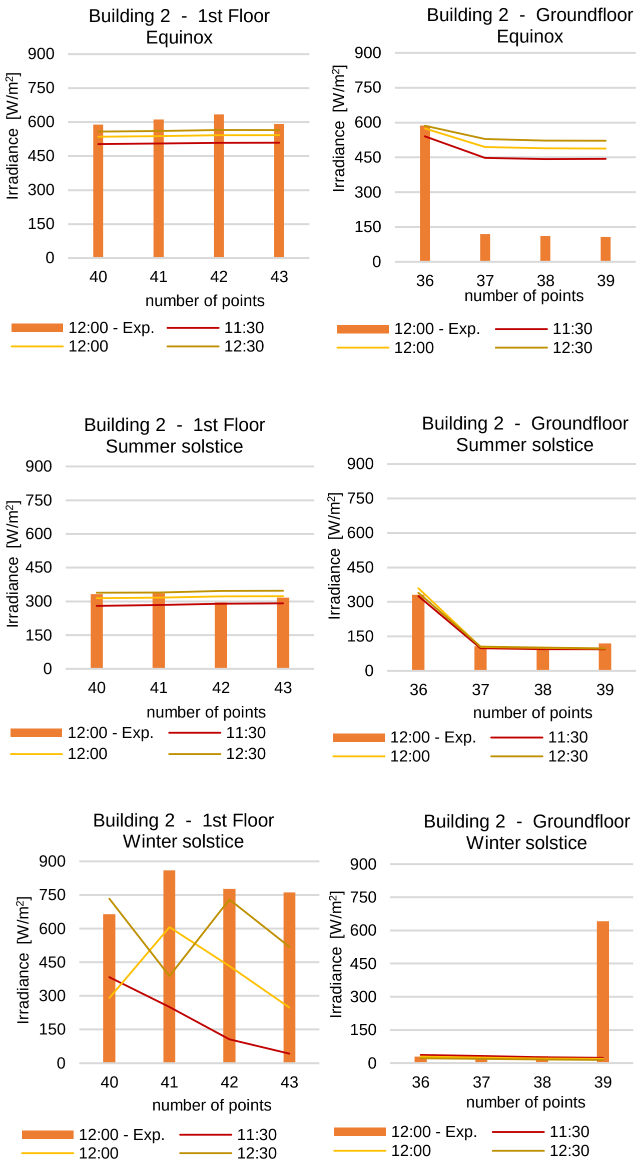


Figure 5.5 - Irradiance in Building 2 at the equinox, summer solstice and winter solstice.

Nevertheless, at the summer solstice, the numeric values are similar to the experimental ones. Lastly, at the winter solstice, we can verify that the numeric values are similar to the experimental ones only for the ground floor. The divergences shown at the first floor are mainly due to the fact that at this time of the year the sun follows a low trajectory. Given that Building 3 presents identical features to Building 2, namely orientation and the presence of a balcony, the simulation results are identical as well. As for Building 1, the model presents a good performance when compared to the other buildings, independently of the period of the year under analysis. This is mainly due to the fact that the façade is facing north and never receives direct solar radiation, rather receiving only diffuse solar radiation from the courtyard and the façades from Building 2 and 3.

The simulation model presents a better performance at the summer solstice for every hour analysed (9:00 AM, 12:00 PM and 3:00 PM) comparatively to the analysis at the equinox and winter solstice.

5.2.1. Model Discretization

To better understand the importance of model discretization, a greater level of detail was set on the discretization (0.50x0.50m^2) of the ground floor of Building 2 at the equinox simulation, as the results obtained at this time of the year were substantially different from the experimental values, namely at 12:00 PM. The experimental values indicate that points 39, 38 and 37 are shadowed by the first floor's balcony, although the simulated values indicate direct solar exposure. After the discretization of the façade from the ground floor of Building 2, (**Figure 4.3**), the affected zone of each of the points turns into smaller size surfaces, as presented in **Figure 5.6**.

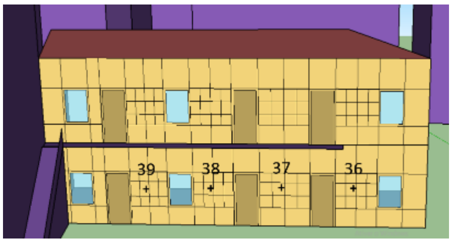


Figure 5.6 – Division of the façade of Building 2 into smaller surfaces.

Figure 5.7 presents the values of the irradiance obtained with the division of the façade in smaller size façades for each of them was attributed a new name, identified by zone. As an example, the zone where point 39 is located was divided into 12 surfaces, identified with the letters A to K, including the specific point to which no letter was attributed. Hence, 39-A is the name of the surface A from point 39's zone with an irradiance value of 75.79 W/m^2.

Observing the results obtained (**Figure 5.7**), it is possible to identify two distinct bands: i) the superior, which presents low values of irradiance which indicate shadow in that zone; and ii) the inferior, with significantly higher values presenting incident solar radiation. Therefore, it is possible to conclude that the best option would be to adopt a detailed model discretization allowing the results to be closer to reality. On the other hand, this would also translate into a significant increase of the duration of the simulation (nearly twice as much).

39-A	39-B	39-C	39-D	38-A	38-B	38-C	38-D
75,79	76,34	76,65	76,81	74,13	74,05	75,08	74,94
39-E	39	39-F	39-G	38-E	38	38-F	38-G
563,77	565,44	567,71	568,19	567,63	567,26	570,82	571,50
39-H	39-I	39-J	39-K	38-H	38-I	38-J	38-K
575,33	578,52	579,19	578,72	578,37	577,39	579,67	581,21

37-A	37-B	37-C	37-D	36-A	36-B	36-C	36-D
76,41	76,41	76,84	77,43	560,42	562,28	564,13	565,31
37-E	37	37-F	37-G	36-E	36	36-F	36-G
570,21	568,48	568,58	566,46	569,34	570,53	570,96	570,61
37-H	37-I	37-J	37-K	36-H	36-I	36-J	36-K
583,67	581,71	580,79	580,80	585,33	584,31	582,91	585,55

50 100 150 200 250 300 350 400 450 500 550 600 650 W/m^2

Figure 5.7 – Variability of irradiance at points on the ground floor of Building 2.

5.3. Calibration of the model

For the experimental calibration of the simulation model (experimental campaigns that took place at the equinox, summer solstice and winter solstice) two statistical indices were used: Mean Bias Error (MBE) and Root Mean Square Error (Cv(RMSE)), which are presented in equation 5.1 and in equation 5.2, respectively.

$$MBE_n(\%) = \frac{\sum_{i=1}^{n}(X_{sim,i} - X_{exp,i})}{\sum_{i=1}^{n}(X_{exp,i})} \times 100\% \quad (5.1)$$

$$C_v(RMSE) = \frac{RMSE_n}{\bar{X}_{exp}} \times 100\% \quad (5.2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{sim,i} - X_{exp,i})^2}{n}} \quad (5.3)$$

$$\bar{X}_{exp} = \frac{\sum_{i=1}^{n}(X_{exp,i})}{n} \quad (5.4)$$

Equations 5.3 and 5.4 correspond to intermediate calculations necessary to determine the Cv(RMSE), where: $X_{sim,i}$ corresponds to the simulated data for the time period i; $X_{exp,i}$ are the experimental data for the time period i; $\bar{X}_{exp}$ is the average experimental value; and n is the number of input data. The parameter Cv(RMSE) is a normalized measurement that determines how the simulation values fit the experimental values, considering the positive and negative differences. Lower values of Cv(RMSE) indicate less dispersion between the simulation and the experimental results.

Table 5.2 -Values of Cv(RMSE) and MBEn for the three simulations

Day	Hour	Courtyard		Building 1		Building 2		Building 3	
		Cv(RMSE)	MBEn	Cv(RMSE)	MBEn	Cv(RMSE)	MBEn	Cv(RMSE)	MBEn
Equinox	**09:00**	48,06%	-8,99%	24,10%	-9,26%	30,77%	7,98%	53,99%	-23,41%
	12:00	47,78%	-23,14%	6,07%	1,04%	51,54%	16,34%	55,32%	0,18%
	15:00	64,88%	-40,31%	11,52%	-0,12%	50,00%	-35,22%	15,99%	-11,12%
Summer Solstice	**09:00**	56,04%	20,39%	32,93%	0,44%	43,16%	15,43%	27,44%	15,17%
	12:00	37,95%	1,04%	17,32%	-6,39%	7,71%	-0,16%	35,11%	-0,83%
	15:00	37,75%	-6,91%	18,41%	5,20%	17,39%	-12,05%	17,14%	-14,37%
Winter Solstice	**09:00**	91,80%	83,92%	45,43%	-32,24%	54,40%	-9,57%	216,54%	-74,96%
	12:00	34,47%	5,78%	36,06%	-33,57%	61,58%	-35,66%	66,09%	-29,48%
	15:00	35,77%	23,13%	66,97%	65,42%	21,97%	-4,12%	29,89%	-23,85%

The MBE parameter measures the proximity between the numerical and the experimental values. Using this index, it is possible to verify the model's tendency to overestimate and/or underestimate the values of irradiance.

According to **Table 5.2,** it is clear that the summer solstice campaign has lower Cv(RMSE) and MBE rates compared to the others, which means that there is less dispersion between experimental and simulated data. Taking into account the values obtained for the parameters that evaluate the modelling error, it can be concluded that numerical results are best adjusted to reality at 12:00 PM of the summer solstice.

In general, it appears that Building 1 has better performance compared to the other elements, given that it never receives incident solar radiation. It can be concluded that the simulation model presents significantly better results for the summer solstice campaign and worse results for the winter solstice. This means that, for the phases of the year when the sun is at a relatively low height, the details of the surroundings of the case study, namely, the neighbouring buildings, are crucial for the good performance of the simulation.

5.4. Analysis of the solar potential on the windows

As an example of application of the previously simulated model, the solar potential on the windows of Vila Luz buildings was assessed.

Simulations were made for each campaign day, using the weather file from IST, so that afterwards an analysis on the radiation arriving to the windows though the different periods of the year could be performed. The amount of energy received on the windows depends on their existing area and also on their spatial orientation. Building 1 has an area of 21.6 m^2, while Building 2 has 4.35 m^2 and Building 3 has 37.25 m^2.

The intensity of the radiation received on the windows during the equinox is similar between the different levels of the building, as can be seen in (**Figure 5.8.a)**), since during the Equinox the sun is in at an intermediate height, where both floors receive similar amounts of solar radiation.

Both Building 2 and Building 3 show values superior to Building 1 due to their orientation (Southeast). Since Building 1 is facing North it only receives energy on the windows from the reflection of the solar radiation arriving on the other two buildings and on the courtyard. During the summer solstice (**Figure 5.8.b)**), it is possible to see a larger time interval where the windows receive energy from the sun, since the summer days also last longer. However, on Building 2 and 3 the amount of energy diminishes during this period of the year, as the sun is located higher in the sky and thus the balconies cast a longer shadow on the windows.

During the winter solstice (**Figure 5.8.c)**), it can be seen that the time period during which the windows receive solar energy is also smaller when compared to other days, since the days become shorter during winter. The windows on the superior levels show values considerably higher than the ones obtained on the ground floor, considering the neighbouring buildings cast shadow on the lower areas of Building 2 and 3. The intensity of the radiation received on the windows of the ground floor of Building 2 and 3 is similar because both have similar characteristics.

Overall, the maximum intensity that reaches the windows is bigger during winter than it is during summer and the intensity received during the equinox is superior to the one received on a summer day. The variation of solar radiation on the windows, for the same orientations of the building, on a summer and on a winter day, shows the same distribution, determined by the portuguese architect Francisco Moita. [19].

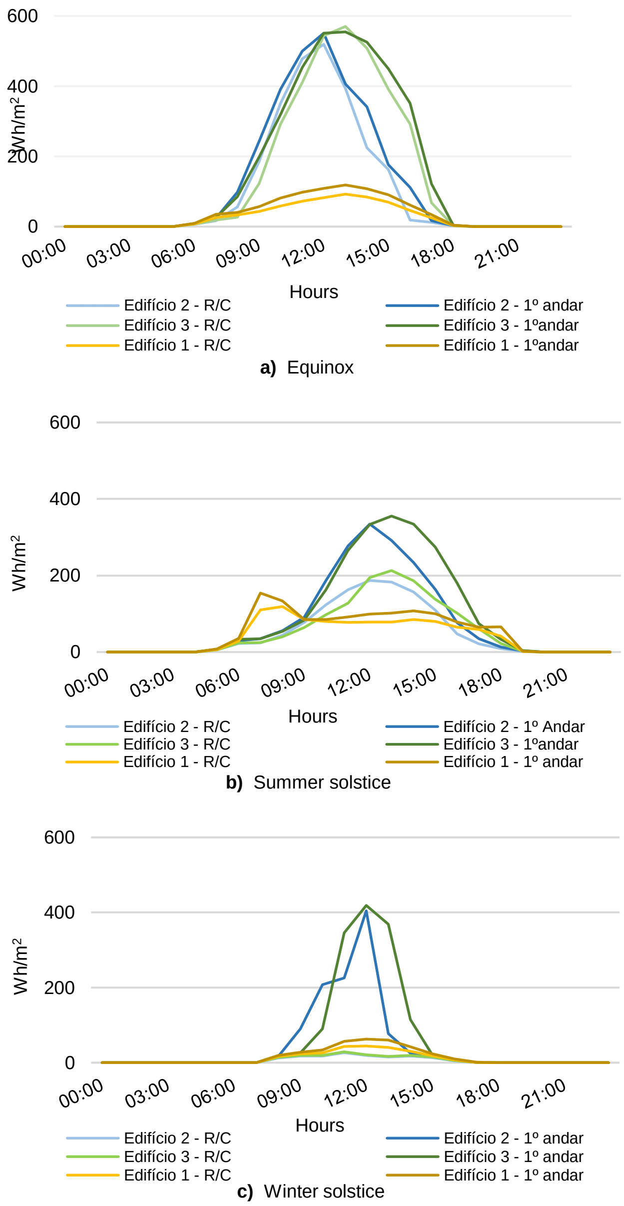


Figure 5.8 - Energy received in the windows of Vila Luz: a) equinox; b) summer solstice; and c) winter solstice.

5.5. Analysis of the yearly solar potential on the windows, façades and roofs

To evaluate the yearly solar potential on the windows, façades and roofs of Vila Luz, simulations for each element were made using the climate file from EPW, which is available on the webpage of EnergyPlus [17].

Figure 5.9 shows a summary of the yearly global irradiation on the windows, façades and roofs. Due to the importance that each construction element has on the comfort of a building, this analysis allows a comparison on the received solar radiation on each different element and an understanding of the potential of each one.

The roofs on the buildings belonging to Vila Luz are the construction elements that receive the most solar energy, since they are at a superior height, practically horizontal and have less shadow from the neighbouring buildings. They have, therefore, a longer solar exposure. For this reason, the applications that make use of the energy coming from the sun are mostly found on the roofs.

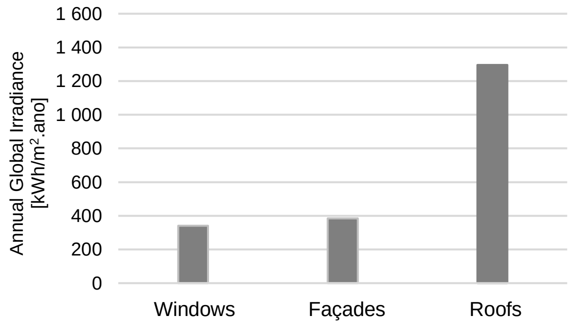


Figure 5.9 – Annual global irradiance in the windows, façades and roofs of Vila Luz

This analysis is relevant due to the increased interest over the last years on the instalment of solar technologies on the façades and windows. The annual global irradiance on the windows shows a value of 341.55 kWh/m^2, on the façades of 385.31 kWh/m^2 and on the roofs of 1295.83 kWh/m^2. Comparing this values to the results obtained by Brito et al. [13] for an annual global irradiance on the façades of 396.79 kWh/m^2 and on the roofs of 1231.21 Wh/m^2, it was concluded that both studies show similar results and, in addition, both studies are made in the city of Lisbon.

6. Conclusions

In this work, the solar potential of a complex building was evaluated, considering not only the intrinsic geometry of the building under study, but also its surroundings. An experimental campaign was carried out and the irradiance measurements was recorded for three specific days - corresponding to the days of the summer and winter solstices, and the spring equinox -, and at three different time periods of the day - 9:00 AM, 12:00 PM and 3:00 PM. The case study was Vila Luz, in Lisbon, and the solar potential for façades and courtyard was simulated, the impact of different factors on the results was evaluated and the model was calibrated.

Based on the results obtained in the present study, the following conclusions are inferred:

1. The choice of a climate file with the meteorological records measured *in-situ*, or close to the case study, and referring to the day of the experimental campaign (rather than to a standard year), is important when intending to calibrate a simulation model. For example, at 3:00 PM on the summer solstice, there is a Cv(RMSE) of 50.00% and MBEn of -8.80% for the IST file, whereas for the EP file, the error is much higher with a Cv(RMSE) of 76.48% and a MBEn of -41.07%, with an improvement of 34.62% in Cv(RMSE) and 78.58% in MBEn. In conclusion, the use of climatic parameters registered in a weather station as close as possible to the case study, is very important.

2. There is a direct relation between the quality of the results and the characteristics of the 3D model used. As a result, when performing an analysis focused on a building or a set of buildings (in the present study, three buildings were analysed), it is important that the geometry of the model reproduce the real geometry of the object and its spatial orientation The definition of the surrounding environment proved to have an impact on the quality of the results obtained by simulation, especially on the winter solstice. The modelling of the surrounding buildings was simplified by extruding the building footprints polygons using the attribute of the highest height of the building (e.g., chimneys, if any, alternatively to the height of the ridging) hence resulting in significantly different numerical results in façade areas subject to direct exposure to solar radiation. Thus, for future evaluations, the modelling of neighbouring buildings and their elements must be particularly accurate in simulations in the winter months.

3. In case a building or group of buildings that are inserted in an urban environment, it is relevant to consider not only the surrounding environment, namely, of the adjacent buildings, but also the presence of elements belonging to the buildings themselves. This is the case for balconies, which have been shown to affect the quality of the results, especially in the summer solstice (when the sun is higher, causing a greater shading zone on the façades).

4. The characteristics of the elements of the envelope, in particular of the exterior cladding materials, also revealed to be important. The *in-situ* measurement of the solar reflectance of the exterior cladding materials of the buildings' envelope and the courtyard proved to be advantageous, concluding that the use of theoretical values of solar absorptance of a material (in the present case, a surface considered clear) may not be adequate. For the three campaigns, there was an improvement of Cv(RMSE) and MBEn around 23% and 26%, respectively, for the absorptance measured at the site compared to that standardized in literature.

5. The degree of discretization of the model in terms of the façade elements of buildings facing south proved to be essential in obtaining results closer to reality, namely at the equinox, when the sun's trajectory is at an intermediate height. The definition of a more refined grid plays a fundamental role in the precision and rigor of the results obtained. Nevertheless, it translates into substantially

increased work with the definition of the grid, and a proportional increase in the computation time of the simulation (from 26 minutes to 60 minutes) that should not be overlooked.

6. The study of all the variables mentioned and analysed in this study allowed the calibration of the simulation model. For example, Building 2 at 12:00 PM at the equinox shows an error Cv(RMSE) of 51.54% and a MBEn of 16.34%; in the summer solstice Cv(RMSE) of 7.71% and MBEn of -0.16%; and on the winter solstice a Cv(RMSE) of 61.58% and an MBEn of -35.66%. Thus, the simulation model presents significantly better results for the summer solstice campaign and worse results for the winter solstice. These results can be justified by the fact that, in the winter, as the solar height is lower, the shading effect of the envelope is considerably higher, making the detailing of the envelope crucial for the good performance of the simulation. Furthermore, as it was verified in the winter solstice, the simplification in the characterization of the surroundings impairs the performance of the model.

7. From the analysis of the solar potential in the various exterior construction elements of the buildings in the Vila, it was concluded that the surfaces that have the greatest solar potential for the placement of PV are the roofs, with an annual global irradiance of 1295.83 kWh/m^2. Windows and façades have considerably lower values, of 341.55 kWh/m^2 and 385.31 kWh/m^2, respectively, since the time of exposure to direct solar radiation is sufficiently shorter. It was concluded that the consideration of the windows and the façade on the determination of the annual global irradiance results in an increase of 26% and 30%, respectively, when compared to a scenario where only the roof is considered.

In general, the analysis carried out in the present study is relevant not only for studies of thermal and energy performance of buildings, but also for the localization and optimization of solar solutions, namely solar collectors and photovoltaic panels.

7. References

[1] Parlamento Europeu, DIRETIVA 2010/27/UE DO PARLAMENTO EUROPEU E DO CONSELHO de 19 de maio de 2010 relativa ao desempenho energético dos edifícios, vol. L 153, Jornal Oficial da União Europeia, 2010, pp. 13-35.

[2] Comissão Europeia, "Climate Action," 2020. [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2020_en. [Accessed 20 Fevereiro 2020].

[3] SolarGIS, "SolarGIS," 2019. [Online]. Available: https://solargis.com/maps-and-gis-data/tech-specs. [Accessed maio 2020].

[4] A. Chow, A. Fung and S. Li, "GIS Modeling of Solar Neighborhood Potential at a Fine Spatiotemporal Resolution," *Buildings,* vol. 4, pp. 195-206, 2014.

[5] M. Debbarma, K. Sudhakar and P. Baredar, "Thermal modeling, exergy analysis, performance of BIPV and BIPVT: a review," *Renewable and Sustainable Energy Reviews,* vol. 73, pp. 1276 - 1288, 2017.

[6] F. Chen and H. Yin, "Fabrication and laboratory-based performance testing of a building-integrated photovoltaic-thermal roofing panel," *Applied Energy,* vol. 177, pp. 271 - 284, 2016.

[7] K. Bot, L. Aelenei, M. d. G. Gomes and C. Santos Silva, "Performance Assessment of a Building Integrated Photovoltaic Thermal System in Mediterranean Climate—A Numerical Simulation Approach," *Energies,* vol. 13, p. 2887, 2020.

[8] C. Catita, P. Redweik, J. Pereira and B. Miguel Centeno, "Extending dolar potential analysis in buildingd to vertical facades," *Computers & Geosciences,* vol. 66, pp. 1 - 12, 2014.

[9] M. Heidarinejad, S. Gracik, M. S. Roudsari, S. K. Nikkho, J. Liu, K. Liu, G. Pitchorov and J. Srebric, "Influence of building surface solar irradiance on environmental temperatures in urban neighborhoods," *Sustainable Cities and Society,* vol. 26, pp. 186 - 202, 2016.

[10] G. Peronato, E. Rey and M. Andersen, "3D model discretization in assessing urban solar potential: the effect of grid spacing on predicted solar irradiation," *Solar Energy,* vol. 176, pp. 334 - 349, 12 2018.

[11] R. Zhu, M. S. Wong, L. You, P. Santi, J. Nichol, H. C. Ho, L. Lu and C. Ratti, "The effect of urban morphology on the solar capacity of three-dimensional cities," *Renewable Energy,* vol. 153, pp. 1111 - 1126, 2020.

[12] R. Machete, A. P. Falcão, M. G. Gomes and A. M. Rodrigues, "The use of 3D GIS to analyse the influence of urban context on buildings' solar energy potential," *Energy and Buildings,* vol. 177, pp. 290 - 302, 2018.

[13] M. C. Brito, P. Redweik, C. Catita, S. Freitas and M. Santos, "3D Solar Potential in the Urban Environment: A Case Study in Lisbon," *Energies,* vol. 12, p. 3457, 2019.

[14] A. Shiota, Y. Koyamatsu, K. Fuji, Y. Mitani and Y. Qudaih, "Development and Public Release of Solar Radiation Map for Effective Use of Solar Energy Based on GIS with Digital Surface Model," *International Journal of Electrical Energy,* vol. 3, 2015.

[15] LI-COR, "LI-200R Pyranometer," 2020. [Online]. Available: https://www.licor.com/env/products/light/pyranometer.html. [Accessed Janeiro 2020].

[16] F. Dias, "Simulação e calibração experimental do potencial solar de edifícios. Aplicação a um caso de estudo," 2020.

[17] EnergyPlus - Weather Data, “EnergyPlus-Weather Data,” 2020. [Online]. Available: https://energyplus.net/weather-search/lisboa. [Accessed Janeiro 2020].

[18] Meteo Técnico, “Meteo Técnico,” 2020. [Online]. Available: https://meteo.tecnico.ulisboa.pt/. [Accessed janeiro 2020].

[19] F. Moita, Energia Solar Passiva - Volumes 1 e 2, Direcção Geral de Energia, 1988.

[20] G. Peronato, E. Rey and M. Andersen, “3D model discretization in assessing urban solar potential: the effect of grid spacing on predicted solar irradiation,” *Solar Energy,* vol. 176, pp. 334 - 349, 2018.