TOOL FOR ESTIMATING SOLAR RADIATION INCIDENT ON BUILDINGS

Study of Geo-Spatial tool publicly available for use

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Abstract

The latest United Nations data confirm that CO2 is still rising in the atmosphere due to world population and economic growth, although renewable energy generation, and in particular solar photovoltaic, has been increasing exponentially worldwide.

Nowadays, it is increasingly common to install photovoltaic panels on roofs of buildings in the main urban centres, as a way to take advantage of the available area in the roofs and thus allow the distributed and local generation, near the consumption points. However, due to the heterogeneity of urban geometry, characterizing the generation potential is a complex task.

This dissertation aims to test the use of the open-source City Energy Analyst (CEA) tool, an urban energy consumption modelling tool, to characterize the generation potential in an urban environment. For this, a literature review is made about the different methodologies that can be used to identify the generation potential. Below is a detailed description of the use of CEA to simulate solar radiation on the roof of buildings in Lisbon. Finally, comparisons are made for three case studies, based on data available in the literature, and data provided by municipal agencies for Lisbon and Oeiras. The results demonstrate that the results of the City Energy Analyst simulation tool present values comparable to other data sources and thus it can be concluded that the tool can be used to simulate the potential of PV installation in urban environment.

Keywords: Solar potential, urban modelling, City Energy Analyst, Geographical Information System (GIS).

Resumo

Os mais recentes dados das Nações Unidas confirmam que se continua a assistir ao aumento de CO2 na atmosfera devido ao crescimento populacional e económico mundial, apesar da geração de energia renovável, tenha vindo a aumentar exponencialmente no mundo.

Hoje em dia, é cada vez mais comum instalar painéis fotovoltaicos em telhados dos edifícios nos principais centros urbanos, como forma de aproveitar a área disponível nas coberturas e desta forma permitir a geração distribuída e local, junto aos pontos de consumo. Contudo, devido à heterogeneidade da geometria urbana, a caracterização do potencial de geração é uma tarefa complexa.

A presente dissertação tem como objectivo testar a utilização da ferramenta de código aberto City Energy Analyst (CEA), uma ferramenta de modelação urbana de consumo de energia, para caracterizar o potencial de geração em ambiente urbano. Para isso é feita uma revisão da literatura sobre as diferentes metodologias que podem ser utilizadas para identificar o potencial de geração. Em seguida faz-se uma descrição detalhada sobre a utilização do CEA de forma a simular a radiação solar no telhado de edifícios em Lisboa. Finalmente são feitas comparações para três casos de estudo, com base em dados disponíveis na literatura, e dados fornecidos por agências municipais para Lisboa e Oeiras. Os resultados demonstram que os resultados da ferramenta de simulação City Energy Analyst apresentam valores comparáveis com as outras fontes de dados e dessa forma conclui-se que se pode utilizar a ferramenta para simular o potencial de instalação de PV em ambiente urbano.

Palavras chave: Potencial solar, modelação urbana, City Energy Analyst, Sistema de Informação Geográfica

Table of Contents

List of Figures

List of Tables

1 Introduction.

The earth's dependence on the sun as a source of energy has been documented since the prehistoric era and today this is no different. What has changed, however, is the means and mode of harnessing this abundance of natural energy the sun showers earth perpetually. Today many modern building and homes are equipped with solar panels on the rooftops to utilize this free source of clean energy, although its availability may be inconsistent at times, there is no denying the fact that solar power is the only source of electricity generation that has the minimal environmental impact. With zero fuel cost and its immunity from spikes in fuel prices, solar power has the potential to make the world move towards a cleaner, sustainable future.

1.1 The current state of the environment.

With the rise in power generation from renewables on an exponential rise and energy efficiency at the core of every modern product that is designed. The status of the earth's climate and environment is expected to be much cleaner and greener, particularly with various strategies and initiatives put forth and are in effect by the European Union such as the EU 2020, EU 2030 etc. and the United Nations' Paris Agreement, etc. However, the real condition of the environment is much further from it, the issue of climate change and the rise in $C0_2$ still persists. According to studies and research data provided by the UN emissions gap report, the collective global endeavour to fight climate change is way off its target as the data shows a rise of CO_2 emissions despite implementing various unified scenarios, strategies and initiatives.[1] The main reason for this increase in CO_2 levels can be attributed to economic growth since 2017. From 2014 to 2016 the world CO_2 emissions in regard to industry and power generation were significantly stable while the economic growth globally was increasing gradually. By 2017 this resulted in an increase of 1.2% in emissions due to the steady increase in higher GDP[1]. Though this increase may not seem very significant, the real problems arise from the fact that in order to keep the global greenhouse gas emissions below the target limit set by the UN, it needs to reduce by 55% by 2030 from the current state. Which means every nation must increase the rate of their strategies and initiatives by five times for it to be effective.[1] While the EU must cumulatively work together in order to bring the emissions down, Portugal is at a much better position than many of its other EU neighbours

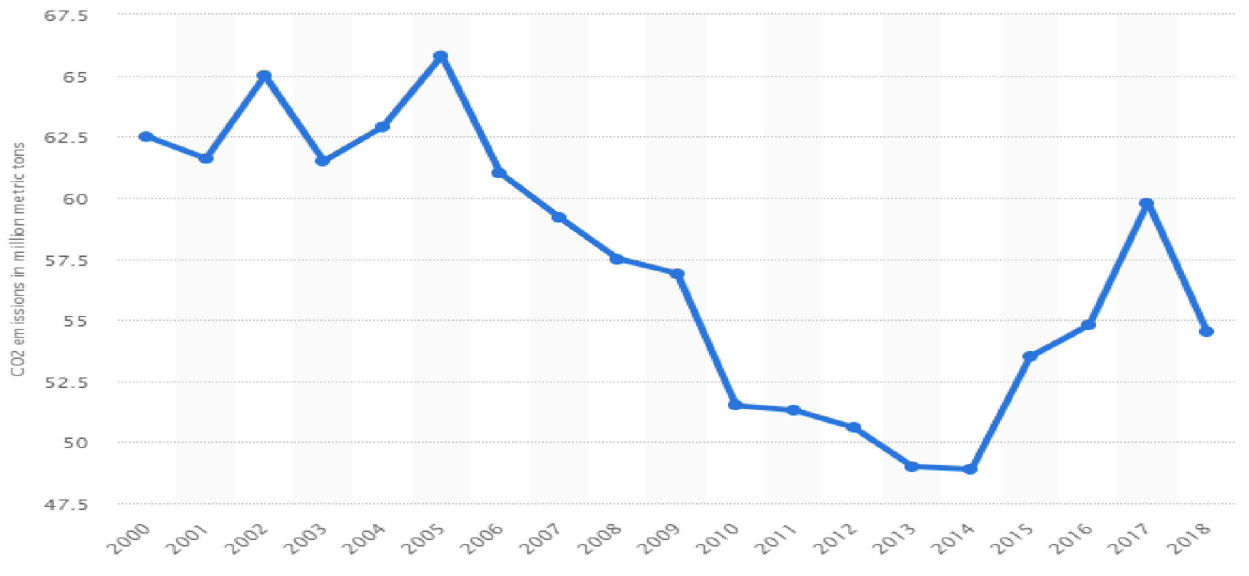


Figure 1: CO2 emissions of Portugal from 2000 to 2018[2]

as suggested by reports from 2018 (Figure. 1). Therefore, to meet the goals set by these energy initiatives in reducing Greenhouse gases is to promote and develop a much further reliance on renewable energy source for power generation and use. One such readily available but underutilized power source is the use of solar energy in the residential sector.

1.2. Solar Energy

The market for solar energy-based solutions is showing substantial growth, credit to the immense technological improvement solar panels have seen it past years. The global installed solar capacity has risen radically and has supposedly reached 227 GWe in 2015 followed by a further increase up to 480 GWe in 2018[3] as reported by the International Renewable Energy Agency (IRENA). This insurgence of efficient solar technology has marked a rise in self-generated energy globally primarily due to the price drop in installing PV systems. Figure 2 below shows the trend of silicon PV cells prices in recent times.

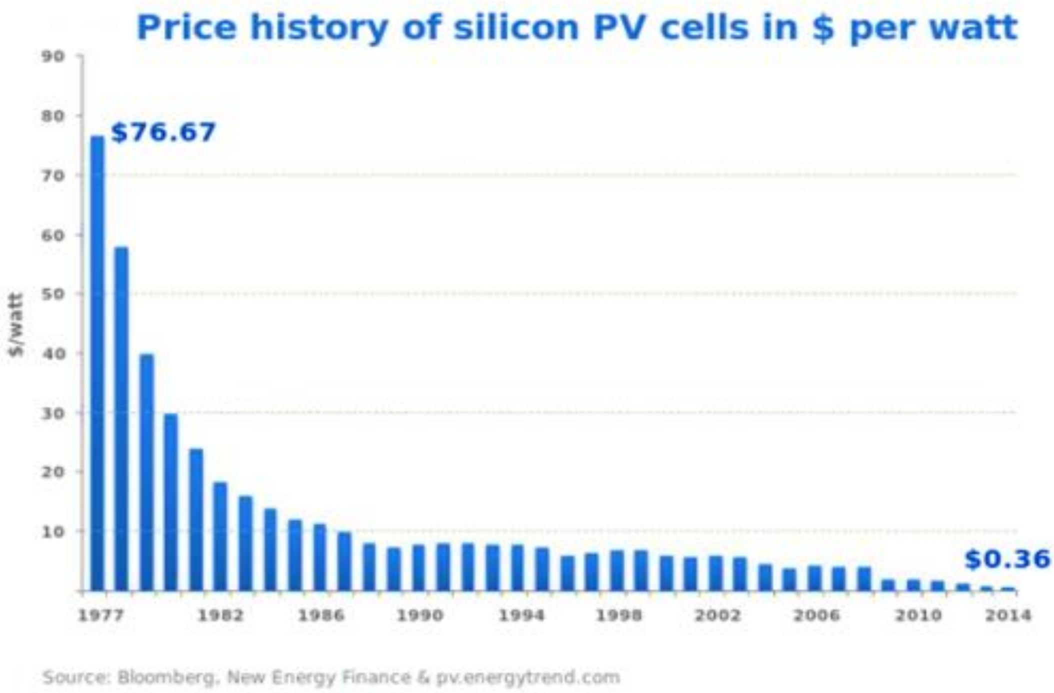


Figure 2: PV cells price ($/Watt) history from 1977 to 2014

Through its escalating popularity in addition to its economic viability, PV cells are expected to be much more efficient and prominently used in the years to come. However, one of the main energy sector that -though having markedly risen in utilizing solar energy for electricity generation- but still has the least impact in total electricity production from solar is the residential sector. It attributes to a very small portion of the total energy consumption in Portugal. As of 2017, the energy produced through renewables in Portugal were mainly from wind power contributing to about 21.6% of the total production, followed by hydropower attributing to 13.3%, bioenergy at 5.1 %, solar at 1.6% and finally energy generation from geothermal energy at 0.4% of the total. Data of 2017, therefore, proves that although solar power is considered for energy generation it still isn't very impactful. Furthermore, of the 1.6% that solar power contributes to the total energy production most of it is mainly industrial. The geographical location of Portugal greatly favors the installation and use of small scale solar power systems, with an average of 2000 to 3000 hours of sunshine per year[4], hence many commercial solar power plants are planned (about 31 new power plants) to triple the total solar energy production up to 1000MW by 2021[5].

The fact remains, with such high investments in solar power production this is mainly at an industrial scale and while the majority of buildings across the residential sector does not opt for its own power generation solutions given the favorable geographical conditions of Portugal. This could be due to the fact that most residents are unaware of the solar potential of their dwellings.

1.3 Objective and Outline of the Thesis.

There are many readily available solar charts and atlas that can easily provide the overall average solar irradiance incident on a particular region. Very few exist that can give reliable data on the solar potential of specific buildings in a given area, these are mostly available for a certain fee. This information is vital for building owners and tenants alike, should there exists such a source, it will allow many to determine whether it is worthwhile to invest in a solar energy system for their power consumption.

This thesis focuses on actively utilizing a new available open-source tool, which mainly is an Urban Building Energy Modelling (UBEM) tool and as such has the capability of running solar irradiance analysis on building rooftops. Thus, the work carried out here is to understand and utilize this tool at some neighbourhoods around Lisbon, Portugal. Mainly to understand, how to familiarize oneself with tools and use them effectively in order to obtain reliable information on the solar energy potentials of any building in Lisbon.

This fundamental tool in question is **City Energy Analyst (CEA)** developed in collaboration with ETH Zurich and SEC (Singapore ETH Center).

Figure 3: Analysis tool used in this thesis

To realize the objective of the thesis, the following procedure is maintained;

i. Understanding the tools: to use the available literature and online information to under how the tool operates. Specifically, what type of input is necessary and how to these inputs must be structured for the tools to run the simulation. A sample simulation is carried on a small neighbourhood in close proximity to Tecnico.

ii. Compare the results with theoretical data: In order to better understand the reliability of solar potentials produced by the tools, the results are compared with highly accurate LIDAR (Light Detection And Ranging) based data available in the literature for a region around the city.

iii. Compare the results with Municipal data from Oeiras: Similar to the previous procedure, this step compares the solar potential output of the tools against Municipal data collected in the neighbourhood of Oeiras.

2 Background Study.

2.1. Building Height Estimation.

To estimate the solar irradiance incident on any kind of structure it is essential to first determine its height. It is one of the highly vital sets of input data for such analysis to be effectively carried out. With the aid of structural heights, various features such as incidence angle, the hourly estimate of radiation over the course of the day and also observe the effect of shadows on a building.

One study presented by Feng Qi et al, primarily focused on developing a simple yet effective method on obtaining building height based on remote imaging and measurement tools of Google Earth.[6] According to Feng's studies of existing solutions that utilize high-resolution stereoscopic Synthetic Aperture Radar (SAR) images, Digital Surface Model (DSM), Digital Terrain Model (DTM), etc. are highly accurate methods but are rather much more complex. The model developed here is much easier to produce and makes use of the tangent function of shadow and building height.[6] However, this model must be used cautiously, as due to its simplistic nature it gives an error of about 15m when used on high-rise buildings. The study also details three fundamental tests to ensure the building images selected for the analysis are clear, to assure the accuracy of the results of estimation.

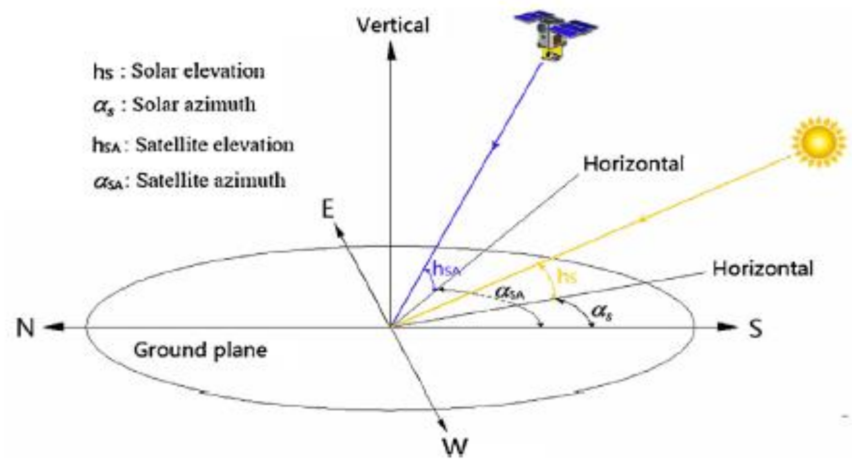


Figure 4 : Satellite elevation & azimuth in relation to Solar elevation & azimuth.

These tests are as follows; building & its shadow test, slope angle test and solar elevation & azimuth tests. The test for the building and its shadow is mainly to guarantee that the selected image of a building has at least one clearly visible vertical edge that can be used to measure its height, similarly, the shadow must be clear and clear-cut in order to be measured. The terrain of a location has an immense effect on how a building projects shadows, therefore, it is essential to calculate the relative error of the building height in terms of positive slope and negative slope. This aspect is calculated using the equations mentioned in the article [6]. Since Google Earth already provides remote sensing images which are taken by the satellite at azimuth and elevation similar or equivalent to the solar azimuth and elevation (Figure 4), this step is omitted.

Using the algorithm by Coper, Duffle and Bourges [6] the solar declination angle (δ) which is much easier to manipulate and use is obtained. After this primary attribute solar declination angle, the rest of the dependent variables such as solar hour angle and solar elevation are defined. An algorithm is then developed to estimate the building height based on celestial geometry[6].(Figure 5)

(Figure 5 shows the relationship between a building and its shadow, this furture relates to the equations below)

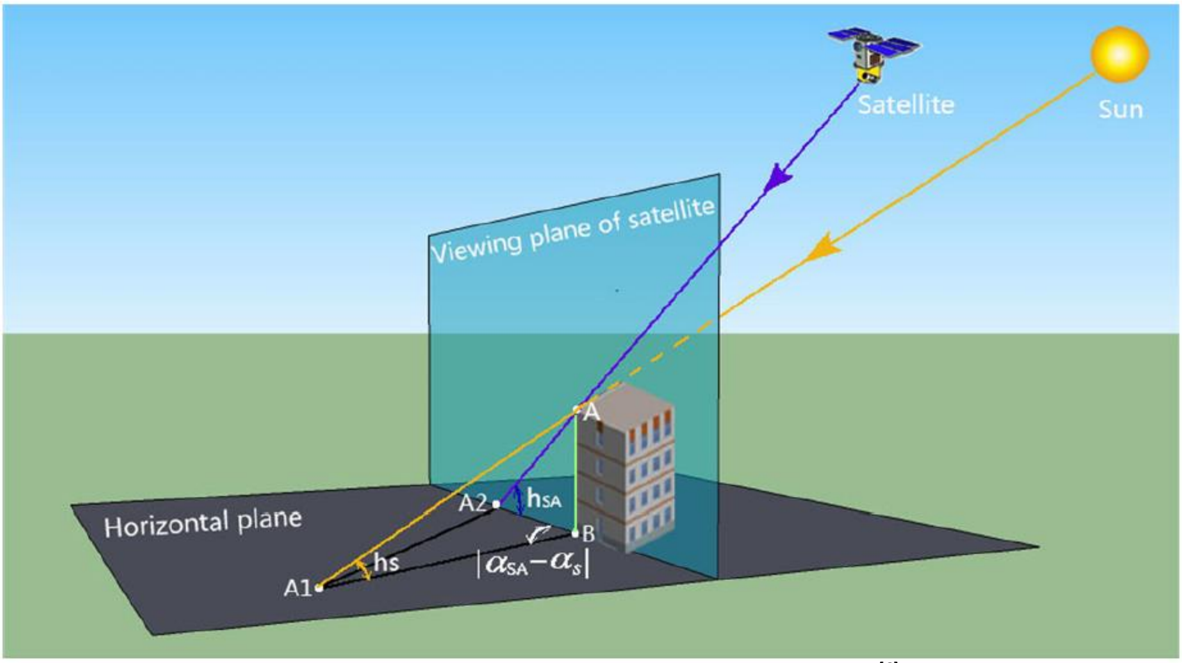


Figure 5 : Relationship between a building and its shadow.[6]

$L_{A1B} = \frac{H}{tanh_S}$ Based on the triangle (A, A1, B) (equation 1)

$L_{A2B} = \frac{H}{tanh_{SA}}$ Based on the triangle (A, A2, B) (equation 2)

$L_{A1A2}^2 = L_{A1B}^2 + L_{A2B}^2 - 2L_{A1B}L_{A2B}\cos(\alpha_S - \alpha_{SA})$ The cosine law based on triangle (A1, A2, B) (equation 3)

Finally, the height of a building (H) is given by;

$H = \tan h_S(L_{A2B}\cos(\alpha_S - \alpha_{SA}) + \sqrt{L_{A1A2}^2 - L_{A2B}^2\, sin^2(\alpha_S - \alpha_{SA})})$ (equation 4)

The algorithm is defined by these 4 equations for estimating the height of a building.

Another study established by Feng Qi et al primarily focuses on the development of a shape coefficient to evaluate building energy efficiency. However, due to the high reliance on geographical based imagery from Google Earth to determine building geometry, a new method of height estimation is proposed. Similar to the above-mentioned literature of Qi, this study also details identical steps to test the data from Google Earth in order to enhance the accuracy of the estimation of building height. Then in order to estimate the building height, a corner-shadow-length-ratio (CSLR)[7] method is proposed that uses Google earth's measurement tools to obtain the ratio of corner shadow(R_{cs}) for a selected building.[7] Based on this ratio the heights of other buildings in the area can be estimated. Giving clear guidelines on how to deem a remote sensing image suitable for this calculations, it suggested that images take on summer be avoided since these images have shorter shadows due to large solar elevation angle in summer.[7] However, the effect on the solar elevation is reversed on images taken in winter, where the shadows are longer due to smaller solar elevation angles. To avoid these misinterpretations of the shadow, only images taken on autumn or spring are to be used, due to their moderate shadow length that allows for a more accurate estimation. One key difference that exists in the CSLR method is the inclusions of using two edges of a building's roof as compared to one edge in the previous study[6], as this research focuses on a region with pitched roofed buildings. Here two (A and B) points of different heights produce the corresponding shadows A_1 and B_1, while points A_2 and B_2 are the remote sensing projections of the two roof points(Figure 6). These three sets of creates two different sets of identical triangles; triangle AA_1C is identical to triangle BB_1C and triangle AA_1A_2 is similar to BB_1B_2. Using these similar triangles the following equation is developed which calculates the ratio of roof corner shadow length(R_{CS});

$$\frac{H_{BC}}{H_{AC}} = \frac{L_{BB_1}}{L_{AA_1}} = \frac{L_{B_1B_2}}{L_{A_1A_2}} \rightarrow \frac{H_{BC}}{L_{B_1B_2}} = \frac{H_{AC}}{L_{A_1A_2}} = R_{CS} \qquad \text{(equation 5)}$$

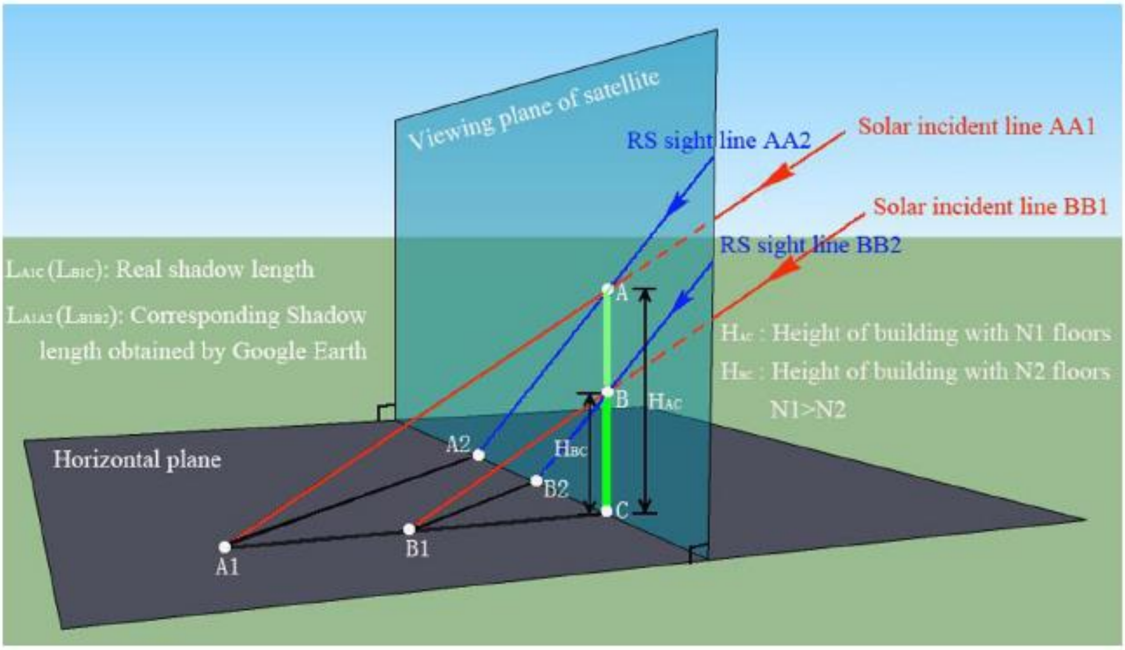


Figure 6 : Visualization of the CSLR model for building height estimation[7]

Here H is the height of the building roof corner, L is the distance from a roof corner to its consequent shadow projection measured using Google Earth[7].

An automated approach for height estimation is proposed by Nada and Monjur.[8] This paper introduces a novel 4 stage approach using VHR multispectral images to estimate the height of the builds. Nada and Monjur developed a ratio-band algorithm that detects the shadow regions by applying a nonlinear mapping function to extract dark pixels from images using the said function.[8] This methodology utilizes the image metadata to extract solar information to automatically identify a buildings shadow region. They further simulated artificial shadows of the building by utilizing the building footprint which was obtained using a graph theory-based approach.[8] The simulation was done to better understand the shadow formation in order to obtain building height accurately as the shadows can be effected by adjacent or connected buildings. Finally, to estimate the building heights from a single VHR satellite image they developed a shadow-fit function based on the Jaccard index. Though the method proves to be very challenging due to its complex algorithm, the results are very reliable. Of the various locals and environments tested, the algorithm seems to have an overall accuracy of 80%. The primary benefit of such a methodology is that it provides a cost-effective and substantially accurate means of 3D reconstruction of urban a reas.[8]

2.2 Urban Solar potential on rooftops of buildings.

With the required data of building heights and terrain data, it is now time to focus on the potential solar irradiance analysis of rooftops in urban areas. Due to the condensed nature of modern cities and their ever-growing demand for power but lack of space for installing sustainable & clean energy solutions. Rooftops provide the most suitable locations for the instalment of PV systems.

A research in the Osaka region of Japan carried out by Yuan et al discuses the idea of extracting small area samples from various parts of the city, wherein the annual solar irradiance incident of the city is measured.[9] The rooftops are selected after running a C++ based algorithm to run a pixel analysis of the roofs of sample areas.[9] These small samples are then further analyzed to find useful area for PV system installation. With the useful PV system area, the annual PV power generation is estimated.[9]

To proceed with the useful PV systems area, first 1km^2 samples of the different zones of the city are extracted from remote sensing images.[9] The solar radiation data is obtained from a practical solar radiation measurement system. In order to gather solar radiation data on various types of inclined planes and orientation the following formulas[9] were utilized;

$$I_{inc} = I_s \cos i + 0.5 I_d (1 + \cos\theta) + 0.5 \rho_g I_g (1 - \cos\theta) \qquad \text{(equation 6)}$$

$$\cos i = \cos\theta \sin h + \sin\theta \cos h \times \cos(A - \mu) \qquad \text{(equation 7)}$$

In equation 6 and 7; I_{inc} is the global solar irradiance on an inclined plane, I_s represents the direct solar irradiance on a normal plane, I_d is the diffuse irradiance on a horizontal plane and I_g is the global solar irradiance on the horizontal plane, these are the various irradiance aspect of the solar radiation. Furthermore θ represents the inclination angle, ρ_g is the reflectivity of the ground surface, *i* is the solar incident angle, h is solar altitude, A represents the solar azimuth while μ is the roof azimuth.

By determining the global solar irradiance and the solar incident angle the sample areas are checked for the optimal PV system inclination angle by using the following formula[9] ;

$$\gamma_{max} = 5.5 + 0.76\varphi - (1.1 + 0.011\varphi)\delta \qquad \text{(equation 8)}$$

Here γ_{max} is the inclination angle of the PV system with the highest daily solar radiation. While φ is the geographical latitude of the location and δ is its declination angle. An algorithm is developed to calculate the solar radiation over the course of a year, the results showed that for the city of Osaka 30^o inclination angle for the PV panel is optimum. Next to calculate the useful area of a PV system Yuan et al proposes the following formulas[9];

$$S_u = S_h \times a \times b \times m \qquad \text{(equation 9)}$$

$$b = U \times G \qquad \text{(equation 10)}$$

$$a = \frac{(S_h S_o S_s)}{S_h} \qquad \text{(equation 11)}$$

Where S_u is the useful area of a PV system to be placed on the rooftop of the sample area[9], S_h is the horizontal projection area of the roof[9]. 'a' is the obstacle proportion of the roof, this parameter denotes the proportion of the roof in which there is no obstruction by any physical object or shadows that may hinder solar radiation[9]. 'b' is the shape coefficient of the roof[9], while 'm' denotes the proportion of number of units[9]. 'U' defines the utilization ratio of the roof due to its style/type[9]. 'G' is the gradient elongation rate of the roof[9]. S_0 and S_s are obstacle and shaded areas of the roof respectively[9]. The shaded area of the roofs of the sample areas was generated with the aid of the software named "Shade of Building 2012"[9].

A similar type of study was performed in Canada, that makes use of Geographic Information System (GIS) software and LiDAR data to obtain an estimate for Photovoltaic potential on rooftops in the city of

Lethbridge. This research is primarily based on GIS due to the flexibility it offers in terms of handling large chunks of data. By utilizing two different types of elevation models (Digital Surface Model DSM and Digital Terrain Model DTM) present within LiDAR metadata; Mansouri et al were able to virtually recreate the region of study.[10] To make the data more usable a maximum value interpolation technique is used to create each roof segment. Furthermore, before integrating both DSM and DTM together for the analysis, the DTM is extracted from the LiDAR data by the implementation of the same interpolation techniques as that of the DSM data. A 1m wide perimeter area is bounded on the rooftops to accumulate for the size of a PV panel system since the Digital Surface Model recreated roofs are not highly accurate in producing correct roof edges.[10] Figure 7 shows the aerial views of the location; 'a' is an aerial satellite image, 'b' is LiDAR point cloud data representation, 'c' is DSM extracted information from the LiDAR data and 'd' shows the building footprints from shapefiles.

With the available data and by the aid of GIS system ArcGIS the inclination of each square meter of a roof is calculated by applying the software's average maximum technique. To include the effect of shadows over the course of the day a shadow analysis is conducted.[10] Allowing for the determination of the roof's area usability based on the movement of shadows over time, by the aid of ArcGIS Hillshade functionality.

The rooftops suitable for PV systems are then filtered from the available data based on their tilt angle, azimuth and incident solar irradiance. Using the Solar analyst available within ArcGIS the amount of solar resource available is evaluated from the DSM; giving results for global, direct and diffuse radiation on the rooftops by taking into account environmental attributes of the location, latitude, terrain elevation, shadow formation, seasonal variation in solar position and steepness.[10]

Likewise, the solar potential on flat roofs was studied by Saadaoui et al. This research was carried out in Ben Guerir, Morroco. Saadaoui first creates vectorized data in CAD form from the orthophoto map of the study region in order to incorporate these into the ArcGIS software by converting the vectors into a geodatabase and assigning a coordinate system.[11] Next, a hierarchical procedure is carried out to analyze the solar potential on rooftops:

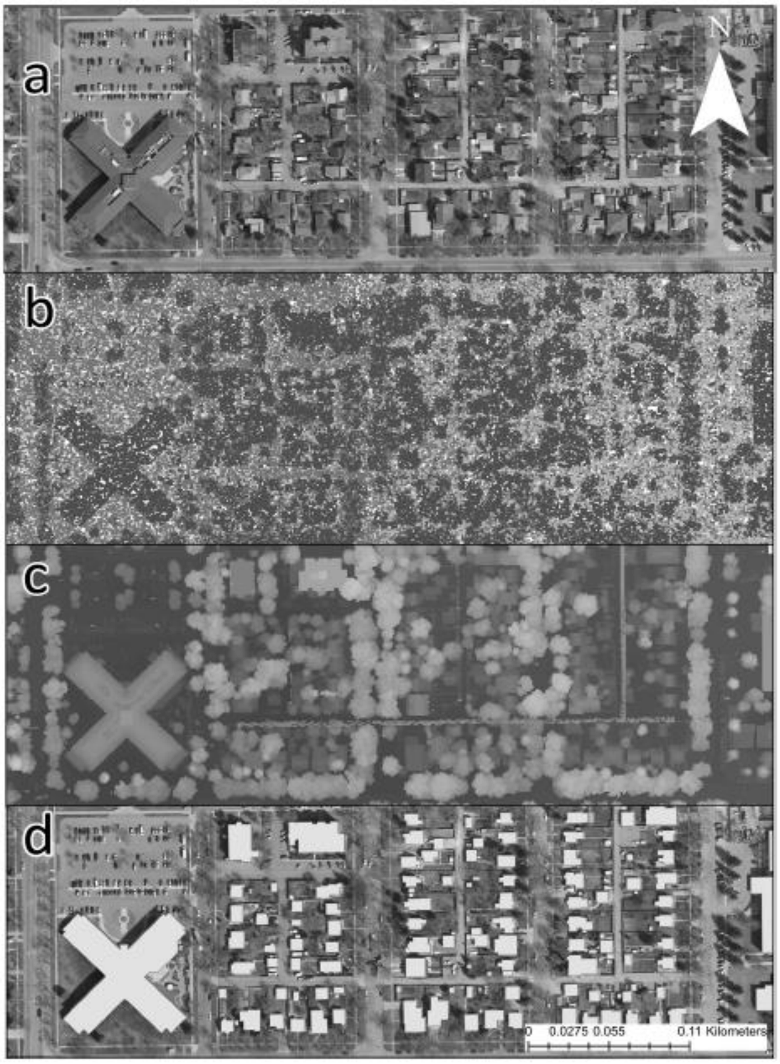


Figure 7: Various type of view of the study area[10]

1- Generating 3D models based on the data obtained from reconstruction of the photogrammetric of the city.
2- The solar analysis is then carried out using the Solar Analyst feature of ArcGIS for the area for the entire year.

To successfully execute the solar analysis in the Solar Analyst, one of its key inputs – the DSM model of the area - needs to be prepared. They achieved this by calculating the Triangulated Irregular Network (TIN) and converting this to the region's terrain model (i.e. DEM)[11]. By applying a bilinear interpolation the accuracy of the final DEM raster is further improved. Finally, with the aid of the raster calculator, the height of buildings is obtained and the DSM is produced by compiling the raster results with the DEM.[11] With all the essential data treated and input ready, the solar radiation analysis is implemented. This analysis is done twice, firstly based on the sun's orientation to find the direct beam radiation; the second is based on the atmospheric attributes of the location to obtain the diffuse radiation.[11] Furthermore, using various geographical properties of the area such as its latitude, position on earth's hemispheres the solar characteristics such as solar declination angle and solar position are calculated.[11] The output of the analysis produces a raster with solar insolation on the buildings, which after applying mask extracting of the building footprint layer on the solar irradiation pattern giving the radiation values of rooftops (Figure 8).

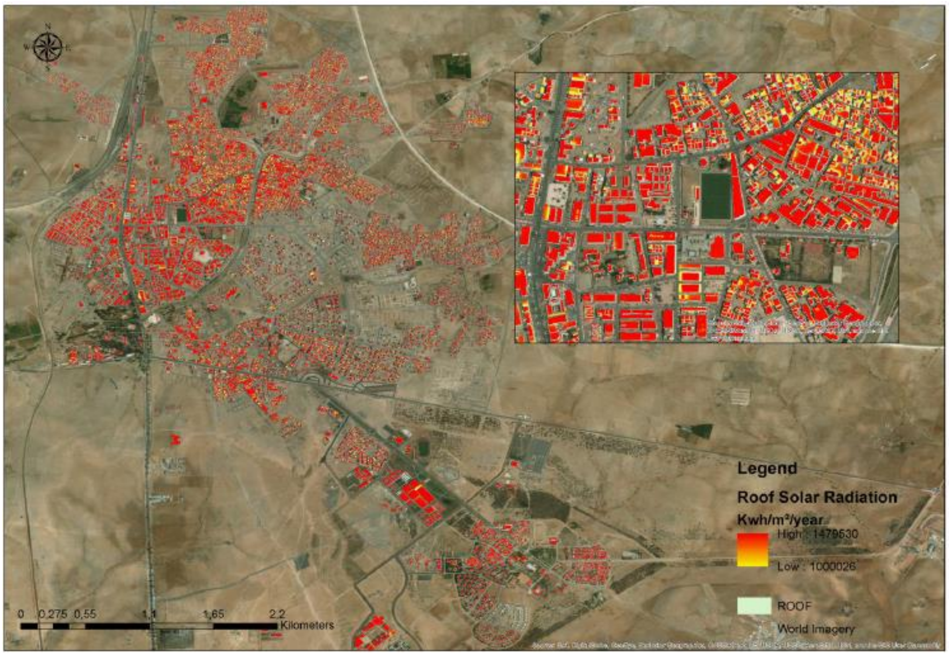


Figure 8 : Results from the Solar Analyst evaluation of Ben Guerir city[11]

2.3 Rooftop Solar Potential in Lisbon.

Equivalent to the above-mentioned experiments and research, Teresa Santos and the team have conducted such an analysis in the city of Lisbon, Portugal. Here Santos et al incorporates Solar Analyst tool of ArcGIS to study area, Av. Novas. Two sets of data that are used are the planimetric building layer obtained from municipal cartography and the altimetric data gather from a LiDAR point cloud of 1-meter resolution.[11] The data were adjusted to be overlayed and represented on the coordinate system that is specifically is implement for Portugal; PT-TM06/ETRS89 – EPSG:3763 (Figure 9).

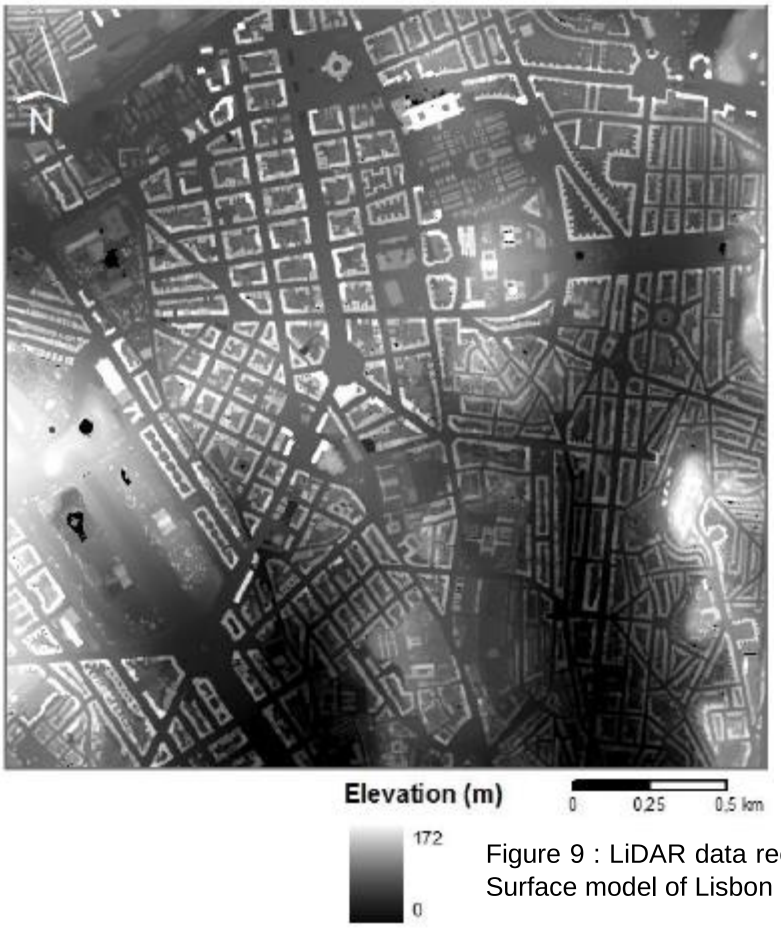


Figure 9 : LiDAR data reconstructed Digital Surface model of Lisbon (Study Area)[11]

As mentioned earlier two essential components to execute Solar Analyst in ArcGIS are DSM and the building footprints.[11] Santos proposes a four-stage procedure to evaluate the solar radiation incident on rooftops of the location;

(i) Naturally, the first step of the evaluation process after gathering the data is to determine the solar radiation incident on the surface of the study region. This is achieved by utilizing the Area Solar Radiation function of ArcGIS. This primarily determines the total incoming radiation for each location of the DSM and produces a solar map; in this case, the output solar map was on a monthly basis.[11]

(ii) Next, the amount of solar radiation actually incident on the rooftop is estimated. For this stage of the procedure, a pixel analysis is applied due to the inaccuracy of the DSM along building edges. Only rooftops with pixel values equal to or lower than 45^{o} slope in the terrain raster are selected for the solar radiation analysis.[11]

(iii) Then, after assessing the rooftops of the stage (ii), the buildings are further analyzed to obtain the most suitable location for PV panels. This is done by considering two criteria, first only rooftops with annual irradiance equal to or higher than 1.68 MWh/m^2 and secondly only roofs with contiguous area equal to or higher than $10m^2$ are considered, mainly due to the fact that it is the minimum required area for a PV system to be viable.[11]

(iv) Finally, to conclude the analysis, a small technical analysis is conducted on PV panels. For this only the conversion efficiency of the panels is considered. By applying the efficiency of the panels to the amount of solar radiation incident on them over the course of a year. The amount of annual photovoltaic energy at each rooftop is determined.[11]

Another work published by Santos et al focused on a different region of the city of Lisbon, Portugal. Here Santos evaluated the solar radiation potential on rooftops of buildings in the Alvalade parish of the city.[13] Unlike the previous study, here the emphasis is also placed on the population of the people living in this parish. By integrating the findings of these both attributes of study two various PV models are proposed to efficiently harness the rooftop solar potential.[13] Similar to the previous study the solar mapping of the area is done by utilizing the planimetric and altimetric data of the place; from these sets of data the building footprint, census block groups and land use map is obtained(Figure 10). The altimetric data for this project was extracted from LiDAR point cloud and digital cartography. The data from LiDAR along with the DTM of Lisbon created from mass points and contours of the cartography are used to create a normalized DSM of the region that gives the height of all objects present above the ground. (Figure 10)[13]

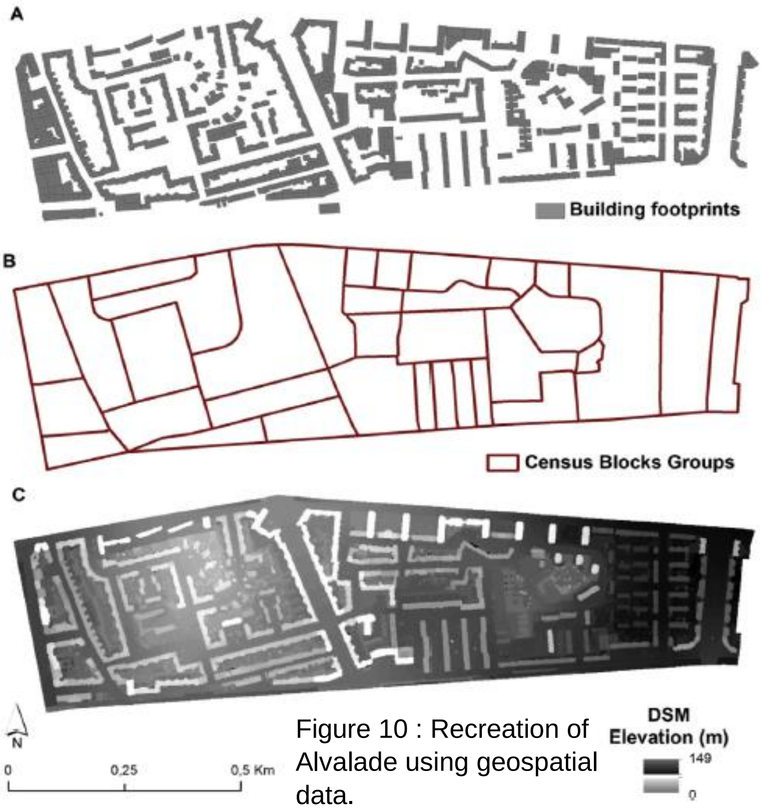


Figure 10 : Recreation of Alvalade using geospatial data.

Three factors are taken into consideration to calculate the optimal setting for assembling a solar energy system, they are as follows: 1) The available incident radiation on a rooftop, 2) The technical aspect of the solar panels to be used and 3) the best suitable location to install the panels. Using the Solar Analyst in ArcGIS as before, the incident radiation on top of each building is determined. The research further carries on with on calculating the roof area available on rooftops for PV panel system and the potential electricity generation of the panels.

2.4 Solar potential estimation tools presently available.

There are many open-source and commercial tools and solar maps available on the web that are capable of estimating the solar radiation incident on a location with a high degree of accuracy. To begin with, **Solar Flux** was one of the earliest implementations of GIS based models built for evaluating solar radiation. It was developed for the ArcGIS formerly known as **ARC/INFO GIS**.[14] Another such early adoption of the solar radiation model for GIS was an algorithm developed with AML script for the commercially available **Genesys**. Similar to these two mentioned solutions, Solei was another standalone solar radiation model that could compute all three aspects(direct, diffuse and reflected) of solar radiation.[14] However, these models were not suitable for estimating radiation over large areas due to them been modelled with simple empirical formulas and many of the calculation parameters been spatially-averaged.

The central aspect that led to the development of modern GIS-based solar radiation models is to eliminate the process of integrating complex GIS functions into mathematical models. This omission therefore reduces the time taken to analyze a location for its solar potential whilst providing accurate results.

Solar Analyst for ArcGIS is one of the most widely used and readily available commercial tools currently in use. The tool allows users to map and study effects of the sun over a geographic area over a time period. It has two sperate functions that allow a user to perform a radiation analysis. (i) The Area Solar Radiation component allows for the calculation of incident solar radiation across an entire geographical area. (ii) The Point Solar Radiation component lets users estimate the amount of irradiance for a specific location of choice.[15] For the purpose of analysis, it also allows users to construct various graphs; such as viewshed map, sun map and sky map.

The **'r.sun'** model is another popular tool for such analysis. This solar radiation tool available in GRASS (Geographical Resource Analysis Support System) GIS is topographic solar radiation model that; similar to Solar Analyst, can compute the direct, diffuse and reflected solar irradiation for a variety of input parameters(day, latitude, surface, atmospheric condition, etc). The theoretical background on which the model is developed is the work carried out by the European Solar Radiation Atlas (ESRA), hence the fundamental equations for radiation estimation reflect European climate conditions. Solar attributes such as declination, extraterrestrial irradiance, daylight length, etc are saved in the map history file of 'r.sun'.[16] The tool can operate in two distinct modes; (i) Mode 1 : for analysis and calculation of instantaneous solar incident angle and irradiance, Mode 1 can be used; (ii) Mode 2 : this allows one to calculate the insolation time and solar radiation for any particular day of the year. To estimate irradiance for any particular duration or interval both the modes can be used simultaneously or independent of each other.[16]

SunSPot is a solar radiation estimation online tool developed by the Australian PV Institute (APVI), primarily for evaluating solar potentials on rooftops of cites across Australia. It was developed as a part of APVI's Solar Mapping study and is funded by the Australian Renewable Energy Agency.[17] The tool takes into consideration solar radiation and weather of the area; even accounts for the shading by near-by buildings and trees. It makes use of 3D building and vegetation models along with meteorological year weather data to calculate the standard monthly and annual incident solar radiation on a building surface.[17] From this information, SunSPot calculates the expected performance of a user-specified PV system accounting for the panel orientation and tilt angle required for the specific user-defined building's roof. However, SunSPot mainly reports results for only the major cites of Australia, that too not for the entire city, in particular, it only gives solar radiation incidence on specific areas of these cities. Figure 11 below shows results from SunSPot from its website. The maps these major city locations are interactive, where a user can tweak some of the map features such as Midday shadows and Solar radiation percentage, user can even change which time of the year this map is based on.

Figure 11: Solar radiation model of SunSPot[17}

Carta do Potencial Solar do Concelho de Lisboa: A tool was developed by Municipia Energy within the context of the European project POLIS - Identification and Mobilization of Solar Potentials via Local Strategies. The use of an Inertial Measurement System has allowed the design of a digital surface model, which also includes the height of the building.[18] The software simulates the incident radiation throughout an entire year. It also factors in the surroundings, in order to identify shading, which could reduce the available solar area.

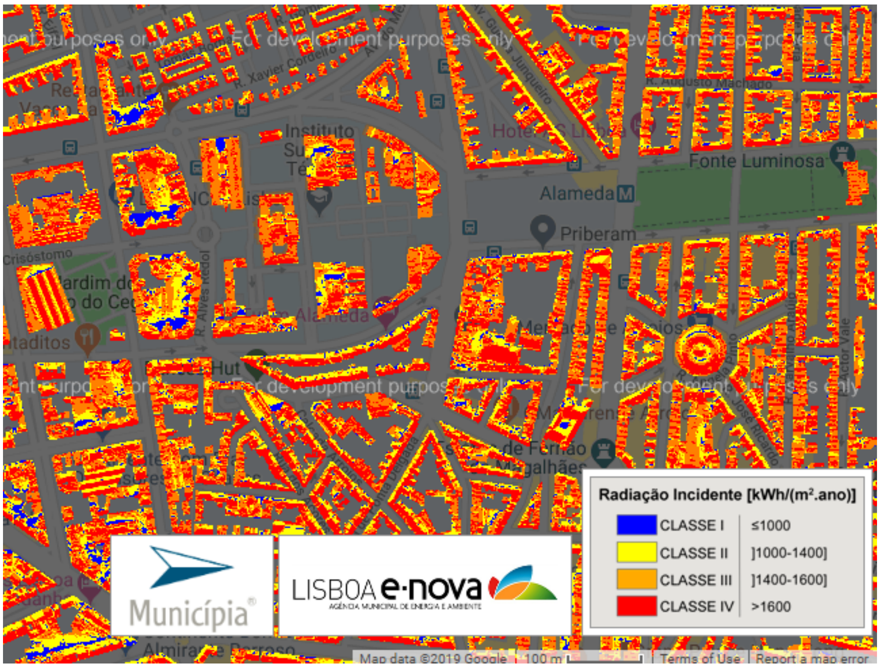


Figure 12 : Carta do Potencial Solar results for Alameda, Lisbon[18]

Global Solar Atlas: Provides Solar irradiance data of cities around the world. Mainly provides averaged solar irradiance incident over an entire city. Developed by SolarGIS based on the solar database and resource it owns and funded by the Energy Sector Management Assistance Program (ESMAP), a part of the World Bank. The purpose of Global Solar Atlas is to offer fast and easy to access global solar data.

2.5 City Energy Analyst (CEA)

A suite of tools integrated to form an urban simulation engine by Jimeno et al. The primary intention being to evaluate various energy efficiency strategies and optimization of energy systems in a city district.[19] City Energy Analyst (CEA) blends energy systems engineering and urban planning expertise into a robust and comprehensive simulation framework. Launched in late 2015 as an open-source package to the public with two fundamental principles; first is to enable urban designers and energy engineering to develop a holistic approach to creating low-carbon cities. Second, to grant researchers of energy and built environment access to a state of the art open-source energy evaluation engine.[19]

Contrasting several of the available approaches and simulation tools, within a single interface CEA can produce a number of building energy demand and estimation model, simulation of conversion, bi-level optimization, multi-criteria assessment and time-dependent visualization.[20] The model facilitates a comprehensive evaluation of buildings, infrastructure retrofit options and the identification of ideal energy generation methods. Plus allowing one to study the energy, carbon and financial benefits of any contemporary urban scenarios. The results of the analysis carried out by CEA is presented in an intuitive interface.[20]

CEA's structure of input is divided into primary and secondary databases; as such if all the required primary databases are in order, the software can be used to generate the required secondary database for analysis. There are four primary databases that must be maintained exactly, to successfully model the desired scenario; these are as follows:

1 - Building footprints (shapefile): This set of data is primarily computer-generated geometry models of actual buildings purposely constructed with the aid of computer-aided design software. These sort of files stores building in the form of geospatial vectors associated with a database table that holds various attributes of a building such as its height, number of floors, its size, etc.

2 - Building age data: Basically a Database file (.dbf) in relation to the building footprint, contains information pertaining to the age of the building i.e. the year it was constructed, the year it has received any sort of renovations and its architectural attributes. Useful when estimating the embodied grey energy and emission due to a building's construction and it's retrofitting (if any).

3 - Building type: Similar to the age database, it is a Database file that holds the information on the purpose of the building. Mainly this file categorizes a building's usage, therefore allowing one to identify whether a particular building is residential, school, hospital, basically the daily usage of a particular building. Primarily, required to run various kind of energy demand analysis as each type of building usage differs from the other.

4 - Weather database: A set of weather data in relation to the location of interest. Information about the climate and weather of the location of analysis is present here. All the data such as sunshine, humidity, temperature, wind speed, precipitation and other climatic information are stored in this as Energy Plus Weather(.epw) format.

The main part of CEA concerning this thesis is the solar radiation module of software which is based on ArcGIS, therefore rooftop solar irradiance is estimated with hemispherical viewshed algorithm similar to it. The algorithm takes into account the radiation attributes, topographic impediments, atmospheric influences, elevation and latitude. Based on the input data and meta-information of height, window size and the total number of floors the tool constructs a virtual 3D geometric representation of the buildings. With these simple models, the tool can swiftly and accurately estimate solar radiation while accounting for nearby reflections and materials. The grid size of each 3D surface representation can be defined by the user and each building model is sub-divided in that grid. The tool performs the calculation at the centre of each subdivision for every hour of the year.

Another useful tool packaged with CEA is Photovoltaic panel electricity potential. Which basically uses the results of the solar radiation model to estimate electricity production by PV panels on building rooftops and walls[24]. The model first identifies the surface areas of buildings that receive enough solar radiation, this value can be defined by the user. Next it estimates the optimal tilt angle, row spacing and surface azimuth of the PV panels based off certain predefined guidelines. Following which the three aspects of solar radiation is calculated the beam, diffuse and reflected radiation on the surface of the panels. The absorbed radiation (S) of the panels is estimated using the model developed by [25] as seen in equation 12 below:

$$S = M\left(G_b R_b (\tau\alpha)_b + G_d (\tau\alpha)_d \frac{1+\cos\beta}{2} + G\rho_g (\tau\alpha)_g \frac{1-\cos\beta}{2}\right) \qquad \text{(equation 12)}$$

$$= (\tau\alpha)_n M\left(G_b R_b K_{\tau\alpha,d} + G_d K_{\tau\alpha,d} \frac{1+\cos\beta}{2} + G\rho_g K_{\tau\alpha,g} \frac{1-\cos\beta}{2}\right)$$

3. Modelling in City Energy Analyst.

At the time of its initial release back in 2015, the City Energy Analyst (CEA) was mainly a toolbox that would evaluate the various type of energy demands for buildings through the integration of ArcGIS ArcScene software. Over the course of time, however, it steady moved away from its ArcGIS integration into its current open-source standalone package. The software demands strict adherence to its database organization in order to perform any kind of analysis.

Like all the literature discussed above, CEA also requires a few common input files similar to ArcGIS and GrassGIS. These are the building footprints (shapefile; .shp) of the area of interest and a terrain raster of the location/district/neighbourhood.

3.1 Preparing and editing input files.

The input databases within CEA are categorized into two: Primary and Secondary databases. The primary databases as the name suggests gives the software vital information about the location of analysis and as such are the main inputs based on which the model will approach its task; it is user input. While the secondary databases can be generated within CEA after the appropriate primary databases are fed to it. Due to its newly developed standalone model still under continuous and rigorous development, it is essential to follow requirements and guidelines set out by the developers in regards to creating the necessary primary input files. This mainly due to the fact that the software is highly sensitive in terms of file format, naming of columns, rows, input database folder and the structure of data held on the input files. Should any part of the primary input database contain an out of line alphabet, symbol, number, etc; the software will completely ignore the entire file and mark it as missing or display an error. The tables below details various types of primary input files required for CEA analysis.

File Name and extension	Explanation	Type of data
district.shp	The building footprints of area of interest and its surrounding buildings.	Heights of buildings, Building Name and Number of floors.
zone.shp	The building footprint of the area of interest.	Heights of buildings, Building Name and Number of floors.
age.dbf	Age of the buildings in zone.shp and its systems (ex: roof, HVAC, windows,etc)	The year of construction and the last year of retrofit of the systems.
occupancy.dbf	Hourly patterns of occupancy of the building	Office, Hotel, School, Residential, etc (mix-use buildings are represented by different shares.)
terrain.tiff	Terrain raster of the district	Elevation data of the region

Table 1 : Primary input databases for solar radiation analysis

File Name and extension	Explanation	Type of data
architecture.dbf	The database containing architectural properties of the buildings in zone.shp	Type of construction material, window to wall ratio, roof type.
internal_load.dbf	Contains the thermal loads of building in the zone.shp	Lights, Hotwater, heat from appliances and people.
internal_comfort.dbf	Holds the thermal comfort threshold data of buildings in the zone.	Upper and lower limits of cooling and heating a building.
supply_systems.dbf	Contains data for evaluating emissions due to a building's operation.	Type of electrical, heating and cooling supply system

Table 2 : Secondary inputs for solar radiation analysis.

It is to be noted that many of the secondary databases (internal load, internal comfort, supply systems) are not need for the solar radiation analysis and PV potential analysis, therefore, they can be omitted.

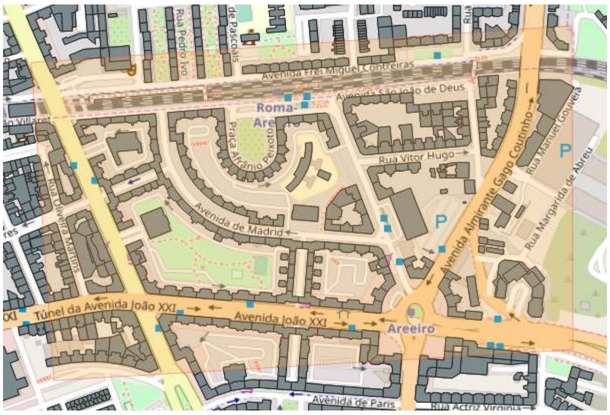
3.1.1 Zone and District files.

As previously mentioned in order to begin the analysis for solar radiation, the local terrain and buildings in the region of interest need to be defined. The first set of Primary databases that are created in this regard are the Zone and District files of the test region. These are created from building footprints of the location, which can be obtained from various sources online such as governmental databases, environment/ecology forums and website or can be generated using most GIS-based software open-source or otherwise. For the purpose of this study, both types of sources are utilized. In this report, the GIS software used is the Quantum GIS (QGIS), an open-source geographical information system

Figure 13: Building footprints of the entire Lisbon area. Data from IN+.

platform similar to ArcGIS.

The first step, therefore, is to prepare/generate the district files from which the zone file can be obtained. First using the available footprint (Figure 13) from research data carried out at IN+, in which all the buildings for the entirety of the city of Lisbon mapped, is used to create a district file. To being with, first, the amount of data available in the Lisbon city shapefile needs to be trimmed as the presence such a huge number of polygons and their accompanying attributes data slows down QGIS, which needs to load and reload the files every time the map is zoomed in/out or panned. This trimming is performed by zooming into the neighbourhood/location of interest and selecting the required area using “Select



a

b

c

Figure 14 (a,b,c): Creating district input file from Lisbon city shapefile.

feature by Polygon" option on the QGIS interface (Figure 14 a). Next with the help of the editing tool of QGIS this highlighted region is first copied (Figure 14 b), then the entire layer of building footprint is selected (i.e. all the building footprints in the entire Lisbon city shape) and deleted. Subsequently, the copied building footprints of the study are pasted back into the QGIS view plane. This is the district file for the analysis. Now the attribute table needs to be corrected in accordance with the requirements of the CEA file/data structure. The structure which must be followed to create the data in the attributes table can be found in Table 3 below.

Data Name	Explanation	Type
Name	Unique ID for each building in the database.	String
floors_ag	Number of floors above ground for the building	Integer
floors_bg	Number of floors below ground for the building. This row of data is valid if the building has basement floors, otherwise, it can be zero.	Integer
height_ag	Total height of the building above ground	Integer
height_bg	Total height of the building below ground. This row of data is valid if the building has basement floors, otherwise, it can be zero.	Integer

Table 3 : Structure of attributes data in district & zone shape file

The data names retain the same format provided in the CEA user manual. Once the district is acquired for the analysis, the zone which is where the buildings of interest are located is defined is created.

In regards to generating the zone shapefile, first using QGIS's export function the district file is used to form the basis of the zone database; keeping the same coordinate system as that of the district file. In this case for the files the **WGS 72 / UTM zone 29 North** is used. Following which the zone file created is then edited using the 'Select feature by Polygon' feature to only include the buildings of interests from the district database. Following similar steps to that of the district shapefile. Once the zone file is pasted back on the region, the attributes table is checked to see if the building data and features are in order; as it possible for the data to get altered during the process. The structure of the attribute(Table 3) for the zone takes the same form as that of the district and therefore, not much is changed here as the zone file attributes are just a smaller version (includes less building) than that of the district.

Figure 15 : Zone file of the analysis region

Figure 15 shows the final results of Zone (denoted in green and always smaller than the district) and District (denoted in grey) generation. The size of the district can be as large as needed but it is kept small in order to reduce computational stress during the analysis of the region

Another process of obtaining the shapefiles for the district and zone databases is to manually generate them through QGIS. Since the Lisbon City database does not include areas that are part of Greater Lisbon area such as Oeiras. This manual method is implemented to create small districts for three neighbourhoods in the Greater Lisbon region; mainly by following the procedure mentioned in [21]. This method takes advantage of the 'Create Layer' feature in QGIS and uses it to produce a new shapefile layer in the form of polygons for each building in the district. After the generation of the district shapefile and following the previously detailed mode of extracting the zone from the district, the required databases are obtained. Based on Table 3 the attribute tables for both are updated with the required data. For all the files the same coordinate system is maintained; **WGS 72 / UTM zone 29 N**.

3.1.2 Raster file: The elevation data of the region.

The land elevation data is obtained from a Raster image of the entire Greater Lisbon area. This raster is obtained from an online resource[22] that has a collection of NASA SRTM (Shuttle Radar Topography Mission) imagery of the world. The raster image (Figure 16) is 30 meters (1 arc-second) resolution digital terrain model (DTM). Due to the wealth of information present in just one raster, it is often impossible to work with such a file with the computational power taking a hit and slowing down the process. Therefore, the raster image is clipped and only the data of the study region is retained for the purpose of the analysis; the rest is removed from the view plane of QGIS. This process of clipping the raster image to a much smaller size pertaining to the study area is achieved with the aid of the extraction feature available under the Raster option in QGIS. To accurately clip the raster extent, the region of interest is selected directly from the view plane. Once the clipped version is produced by QGIS, it now needs to be corrected to the coordinate system on which the zone and district files are referenced. This was done by first exporting, naming the clipped

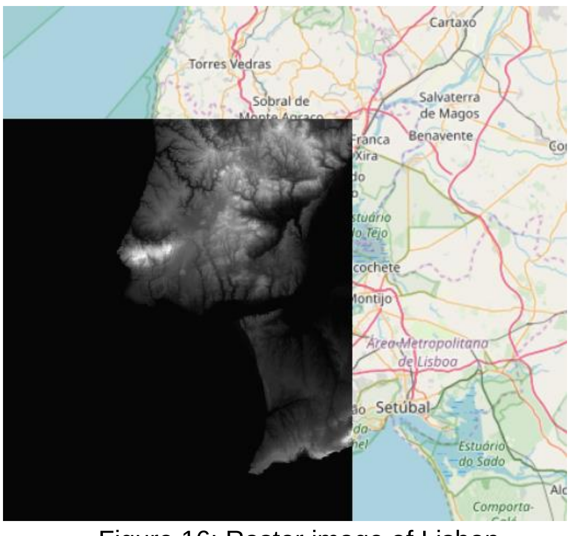


Figure 16: Raster image of Lisbon.

raster extent as ‘terrain’ (based on the CEA database naming structure; Table 1) and selecting the appropriate coordinate system. The results of raster clipping and exporting is shown in Figure 17 below. The raster file in comparison to the

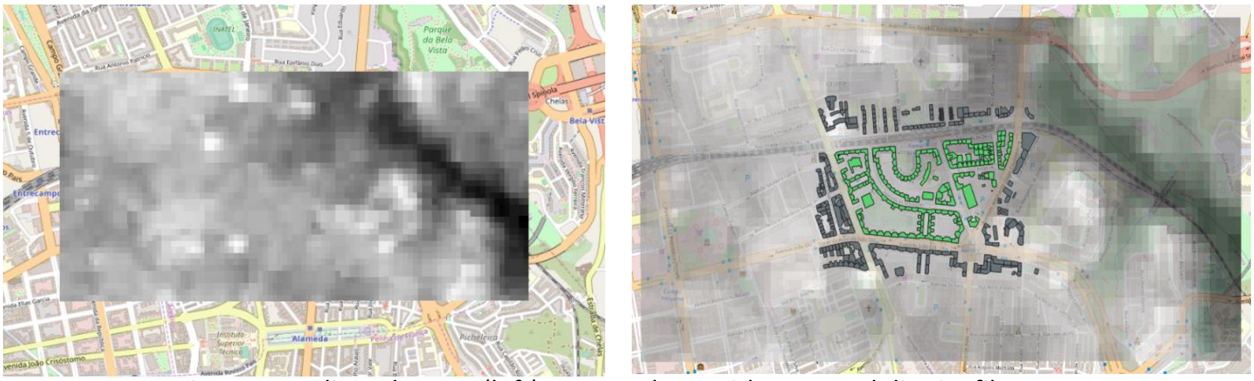


Figure 17 : Clipped raster (left); Raster along with zone and district files

District file is much larger, so as to cover all the buildings present in the district and zone shapefiles. Should the terrain file partially exclude one build of the district database, this will lead to an error on CEA solar analysis. Mainly due to the fact that one of the output results of solar radiation analysis is the incident radiation on buildings for the whole district.

3.1.3 Building properties database: Occupancy, Age and Architecture .dbf files.

The next set of input data that is required to successfully run the solar radiation analysis are the occupancy.dbf, age.dbf and architecture.dbf. Though, the analysis on CEA can be achieved solely on the architecture database of the buildings in the zone. This, in turn, does prevent further analyzing the buildings for PV electricity generation. In conjunction with Table 1, the occupancy file contains the data on the usage of each and every building in the selected zone, while categorizing each building. This usage is defined as a percentage value in the .dbf file (Figure 18); an example for a multi-residential building (the majority of the buildings in Areirro are as such) under the category of MULTI_RES, most building will have a value of 1, denoting that those buildings are only used as residential building. Similarly, if a building has multiple purposes such buildings in the city center that houses restaurant, office, shops, etc all under one roof then its occupancy can be distributed across all the related categories of the occupancy file.

	Name	HOTEL	COOLROOM	PARKING	SCHOOL	OFFICE	GYM	HOSPITAL	INDUSTRIAL	RETAIL	RESTAURANT	SINGLE_RES	MULTI_RES	SERVERROOM	SWIMMING	FOODSTORE	LIBRARY	LAB	MUSEUM	UNIVERSITY
1	B41263	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
2	B41287	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
3	B41230	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
4	B41237	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
5	B41199	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
6	B41221	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
7	B41161	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
8	B41177	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0

Figure 18: Structure of occupancy .dbf file

City Energy Analyst classifies buildings in nineteen different categories (Figure 18), from hotels and hospitals to gym and university. As required by the CEA structure all the categories must be present in the occupancy database for the program to accept it as valid input. For the purpose of CEA, only occupancy.dbf file is enough, the occupancy.dbf is easily obtained by using the export function of QGIS and exporting the zone shapefile and renaming it to occupancy. This is done so that the occupancy file automatically has all the building names, hence by simply deleting the features of the zone (example: height_ag, floors_ag, etc) that also got copied in the attributes table and replacing it with the building category, produces the occupancy file. All the category names are entered in upper-case letters so as to maintain the CEA database structure, else the CEA software produces an error should any of the nineteen categories be missing or aren’t entered in upper case alphabets. Next by the aid of the ‘field calculator' feature in the attribute table each category column is updated, which can also be achieved by manually inputting the occupancy values for each category. Indeed doing so with the test location would be very time consuming as the zone has over 185 buildings that need to be updated for all the nineteen categories, hence the use of 'field calculator' to update each category for all the buildings. Furthermore, since this study is mainly focused on the solar radiation available on rooftops of the building the accurate categorization of the buildings are not necessary (would also be very tough and time-consuming for so many buildings), therefore, all the buildings are set to be fully used multi-residential buildings (Figure 18; only MULTI_RES column is filled with a value of '1').

To generate 'age.dbf', a similar procedure is followed to that of creating occupancy files from the zone files by using the export function. Once this is done, the attribute table for the age file needs to be corrected. Since the file is obtained from zone files, the building names are already present in the attributes. Only the required columns (detailed in Figure 19) need to be added for making it ready for City Energy Analyst.

	Name	built	roof	windows	partitions	basement	HVAC	envelope
1	B41263	2001	0	0	0	0	0	0
2	B41287	2001	0	0	0	0	0	0
3	B41230	2001	0	0	0	0	0	0
4	B41237	2001	0	0	0	0	0	0
5	B41199	2001	0	0	0	0	0	0
6	B41221	2001	0	0	0	0	0	0
7	B41161	2001	0	0	0	0	0	0
8	B41177	2001	0	0	0	0	0	0
9	B41435	2001	0	0	0	0	0	0
10	B41437	2001	0	0	0	0	0	0
11	B41426	2001	0	0	0	0	0	0

Figure 19: Structure of Age attributes table

The age database as aptly named holds information regarding the year of construction/restoration of the building and the year any of the building systems and retrofits were replaced. Using such information CEA can run various analysis on estimating embodied & grey energy and the consequential emissions due to the construction of the building and its retrofitting. For the solar analysis, this does not have much of an effect but is a primary database for CEA simulation to run and as such it is essential. The procedure of creating the age database file is the same as occupancy database (exporting the zone file) in order to preserve the total number of buildings and their unique name, maintaining coherence among all the CEA input files. In the study, all buildings in the area of Areeiro were set to 2001 as their 'built' year, while the rest of the building attributes were set to a value of zero.

In regards to the architecture file for the test area, there are two ways this can be obtained. The first and rather simple solution is to use the inbuilt data-helper tool within City Energy Analyst to generate the files of architecture database (.dbf file). This method requires fully structured occupancy and age files for the software to generate the architecture files along with the district and zone databases. Since CEA is in charge of creating this database through its data helper feature, there is no need for exporting zone shapefile, renaming or editing the structure of the attributes table with QGIS. These processes are automatically executed by CEA data helper which further creates other secondary input databases such as indoor_comfort.dbf, internal_loads.dbf, supply_systems.dbf, etc. The other approach of generating the architecture database files follow the same process as before of exporting, renaming and editing the attributes table in QGIS. This is done by obtaining information regarding the various attributes of a building from government sources or census studies. Table 4 details the required information for the architecture.dbf file based on the CEA's required structure.

Data Name	Explanation	Type
Name	Unique ID for each building in the database.	String
void_deck	The share of floors (in ratio form) in an open envelope	Decimal Number
Ns	The ratio of total floor area that is occupied by tenants	Decimal Number
Hs	The ratio of the occupied floor area that is conditioned.	Decimal Number
Es	The ratio of the occupied floor area that uses electricity	Decimal Number
wwr_x	The average ratio of window to wall in the x-direction	Decimal Number
n50	The air exchange rate per hour at a pressure of 50 pascals.	Integer
type_roof	Roof construction type. (The values and attributes are further defined in the CEA default databases)	String
type_wall	The wall construction type. (The values and attributes are further defined in the CEA default databases)	String
type_win	The window construction type. (The values and attributes are further defined in the CEA default databases)	String
type_shade	The shading system type. (The values and attributes are further defined in the CEA default databases)	String

Table 5 : Structure of architecture database

3.1.4 Weather data of Lisbon.

The weather data in order to analyze the solar radiation on building rooftops is obtained from the weather database of Energy Plus [23] since City Energy Analyst demands the weather data input in .epw format. This data also be obtained from local meteorological sources. As always in order to maintain the acceptable CEA structure, the file is named ‘weather’.

3.2 Organization of database files and folder structure.

Once all the primary databases are gathered, there remains one final task before opening the project in City Energy Analyst. In order to read all the input data correctly by CEA, it needs to be arranged in a certain manner within the folder which will contain all the shapfiles, dbfs, DTM, weather data, etc. Figure 20 shows the way in all these data needs to be set up before opening the software.

All geometry-based input files (district and zone shapefiles) that contain data regarding building height are put in the folder ‘building-geometry’. While database files that hold the building characteristics and properties information are placed in the ‘building-properties’ folder. The folders ‘networks’ and ‘technology’ are a product of executing the data-helper tool of CEA and holds various database files generated based on the primary input files. The DTM of the study region which has been extracted from terrain raster image of Lisbon is placed inside the ‘topography’ folder. Finally, the weather database of Lisbon is put into the aptly titled ‘weather’ folder. As previously mentioned CEA adheres to a strict structure for all its input files, this is also true for all the encompassing folders that hold these input files within the CEA analysis folder. Therefore, the naming of the folders must be similar to that provided in CEA documentation and referenced in Figure 20. Should one file of a particular database is mistakenly placed in a wrong folder instead of its respective folder the software will either completely ignore the file or run into an error during simulation.

Now with all the files and folder appropriately structured and arranged these can be read by the software and solar radiation analysis is commenced.

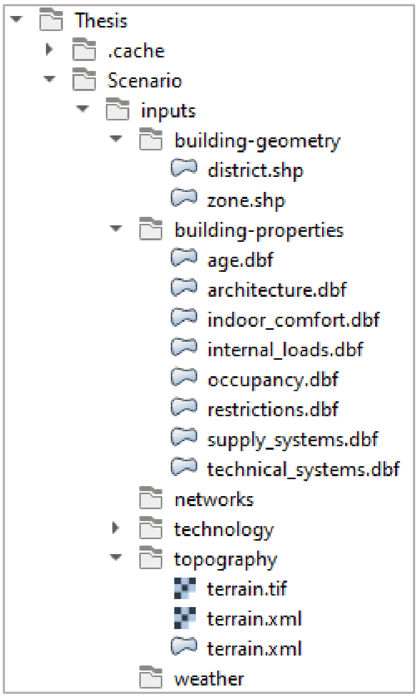


Figure 20: Folder and files organization for CEA analysis

3.3 City Energy Analyst simulation: Solar Radiation and PV electric potential.

The version of City Energy Analyst used for this thesis is version 2.22. Due to its early-access nature, the software model does not run on its own specifically designed user interface but runs on the third-party internet browsers such as Google Chrome or Mozilla Firefox. In conjunction with the browser-based interface, a command window also runs simultaneously in the background that mainly displays source codes based on the processes CEA is running at any given, this is also where most of the error message will be displayed in full context by the software.

On the landing page of CEA, the software offers two option: ‘Open project’ or ‘New project’. The new project option provides users with the ability to generate the primary input files (district and zone) using its data management tool. Though the accuracy of the generated files can not be ensured. If all the input files are structured accordingly, after opening the project CEA will display all the primary input information on its ‘Input Editor’ tab (Figure 21). Where if any input requires necessary revising it can be done, the software also visualizes the district(light grey colour) and zone(dark grey colour) of the area of interest in 3D. Hovering over the buildings display their heights and floors information based on zone and district databases.

Here again, there are two methods of implementing the solar radiation model based on the input data. If a user-generated architecture database file is used as input there is no need for creating the occupancy and age databases. Then under the ‘Tools’ tab in the ‘Energy potential’ feature the solar radiation analysis tool can be executed to run the simulation. However, in the absence of the architecture database, it first necessary to create the occupancy and age databases for primary input. For the study conducted in Areeiro region with 185 buildings gathering information and creating architecture database proved very challenging. Therefore, with aid of the ‘Data-helper’ tool in the ‘Data Management’ tab, the architecture file is generated.

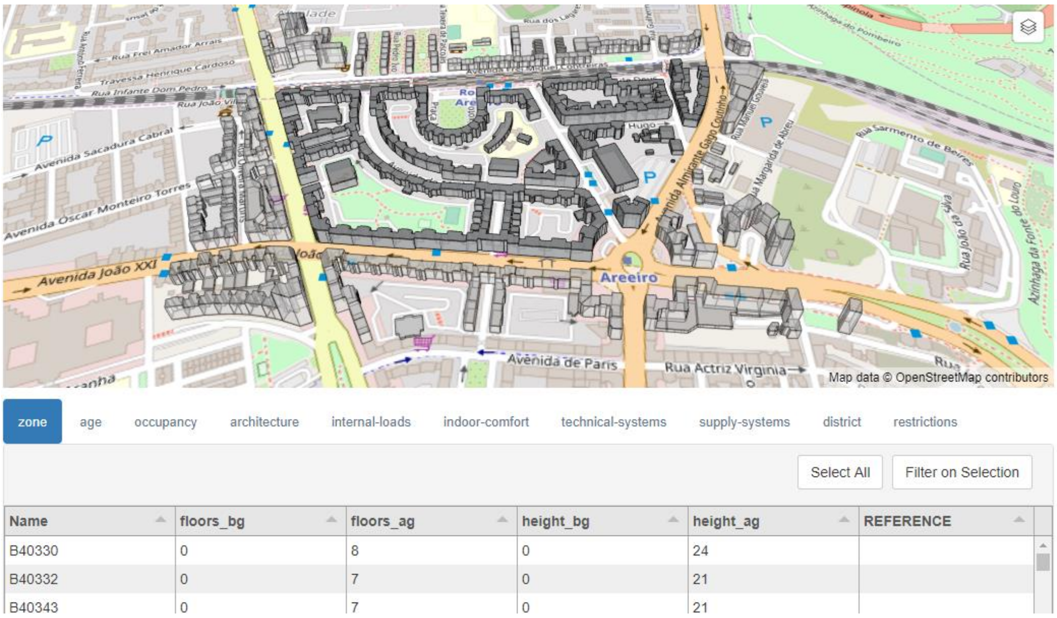


Figure 21: Input Editor in City Energy Analyst.

Before initiating the data helper tool, CEA asks for the region the user wants to run the tool; primarily since buildings properties vary from region to region. Two options are currently available in this, 'CH' which refers to Switzerland default database and 'SG' that represents the Singapore default database. For this study, the Swedish default database (CH) is selected, as CEA developers have modelled this set of information to characterize the European architecture.

After the data helper module has finished the process, the solar radiation tool is prepped for analysis where the various parameter of the tool can be changed or adjusted. However, in its current state, none of the advance setting or options has been altered in order to avoid errors, the simulation is executed with the default configuration. There is an option in the solar radiation tool where any specific building or buildings can be selected to run the analysis on, for this thesis this option was left blank so as to run the simulation on all the buildings present in the zone.

Following the simulation of solar radiation, the Photovoltaic electric potential is initiated. It must be noted that; since for this study in Areeiro the occupancy and age files were separately produced and the architecture database generated from data helper, it possible to run this simulation after solar radiation analysis. The shortage of occupancy and age databases in the input file will require one to create them before continuing with PV electric potential analysis. With the access to solar radiation of the area, PV analysis is accessed from the 'Energy potentials' tab under 'Tools' in CEA. Here there are three different types of PV panels to select from; PV1 : Monocrystalline panel, PV2 : Polycrystalline panel and PV3 : Amorphous Silicon panel. For analysis Monocrystalline panels have been selected as it is the most widely used and economic type of photovoltaics in the market.

After the completion of all the analysis, the results are displayed in the dashboard options on various types of charts.

4. Results and Discussion of Simulation.

Pertaining to the objective of the thesis stated in chapter 1. The results of the simulation are presented and discussed in this section. Using the generated primary input files for City Energy Analyst, an initial test study was conducted in a neighbourhood of Areeiro. Mainly to understand the operation of the tool, how to successfully simulate solar radiation on a large cluster of buildings, followed by the PV panel electric potentials on the rooftops of buildings. These analysis results are compared against the values of 'Carta de Potencial Solar' which also shows the solar radiation incident on building rooftops across all the regions of the city.

Another set of simulations is carried out based on the location based on the study conducted by Teresa Santos et al[12]. For these sets of simulations concerning the work of Santos, three different segments of areas are intensively reviewed. Analysis of these particular sections of Lisbon is done with City Energy Analyst and the results are compared.

The third set of simulation is conducted for three buildings which are located outside the main city of Lisbon but are located within the Greater Lisbon region. These buildings are located between Lisbon and Oeiras region.

4.1 Analysis of results of Areeiro Simulation.

The simulation on Areeiro includes 185 buildings in a zone, due to limitation in computational power only part of the region of Areeiro parish is considered. City Energy Analyst outputs results of solar radiation analysis on its dashboard feature. This aspect of the software displays the results in the form of graphs that displays information in a very comprehensible manner. However, as the number of buildings in this analysis

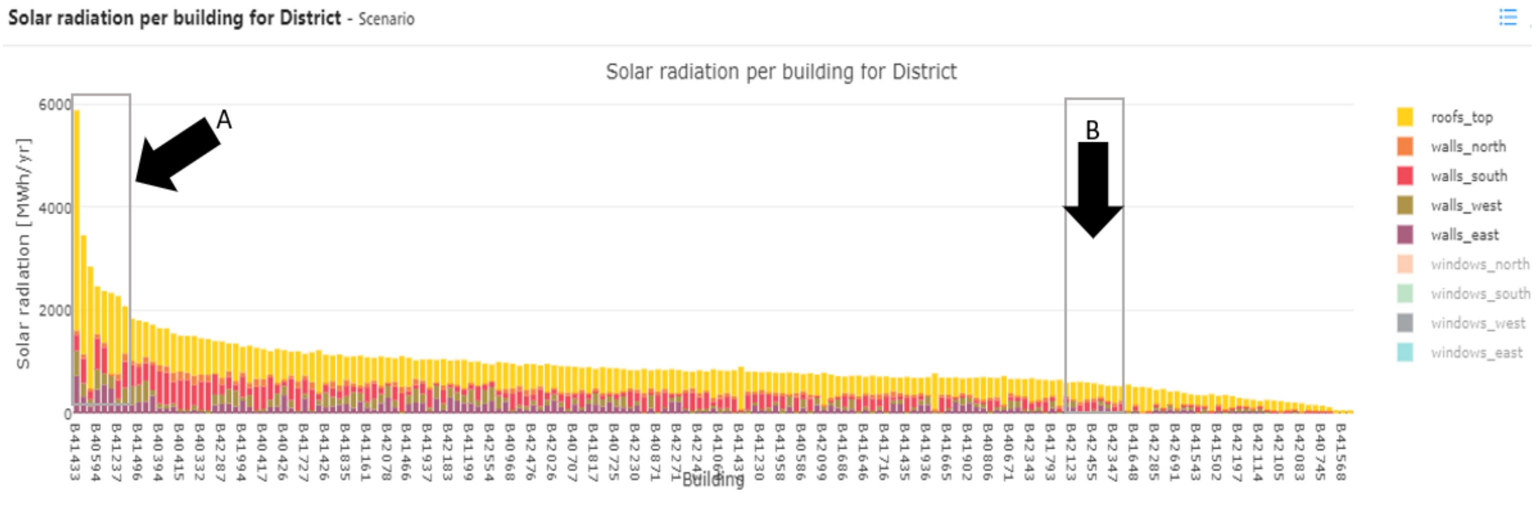


Figure 22: Solar radiation on top of buildings in Areeiro neighbourhood

Is very high, in an attempt to present all the results in one plot the results of the analysis becomes distorted (Figure 22). The analysis also produces RAW data files which can be found in the 'outputs' folder of analysis directory. These files form the basis of the plots that CEA generates in its dashboard to display output results of simulations. The graph shows the incident solar radiation on all façades of the buildings but the main point of interest is the results of the rooftops, denoted by yellow bars on the stacked graph. Since results are automatically categorized from highest total incident radiation to the lowest, for analysis of the CEA outputs two different segments of the results are focused and compared to solar map (Figure 12) available from Lisbon Municipality. Furthermore, all buildings are represented in the graph but the legend does not display all the building names, which makes it harder to directly read the results of the graph for such a high number of builds. Hence, the two selected segments are from the high (A) and low (B) region of the incident radiation results as signified by the arrows on the graph above.

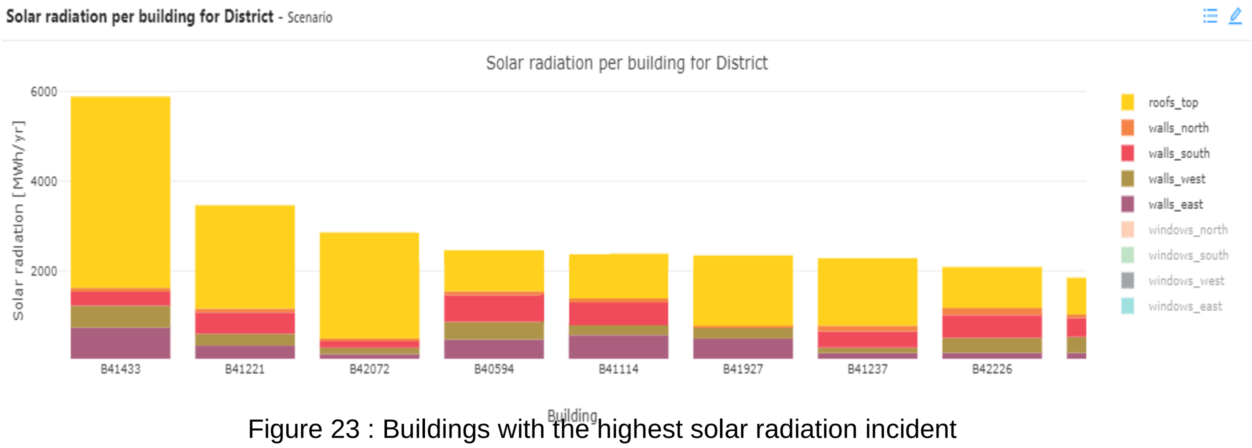


Figure 23 : Buildings with the highest solar radiation incident

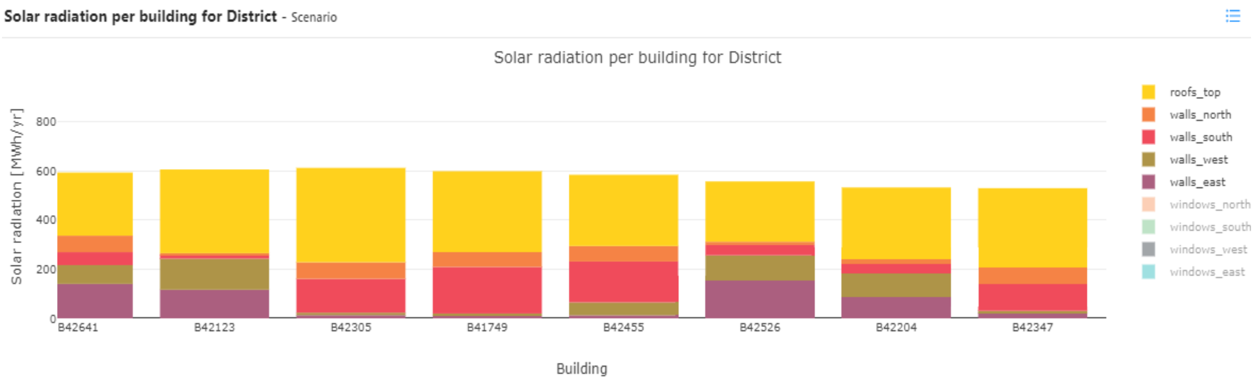


Figure 24: Buildings with the lowest solar radiation incident

The results of the three segments of the solar analysis of Areeiro neighbourhood are presented in Figure 23 and 24. The values on 'Carta de Potencial Solar' are in indicated in a different unit then that of CEA; kWh/(m^2, yr) while the results from the simulation are in MWh/year. A simple division of the area of the buildings selected for comparison with the simulation results gives the values required, as detailed in Table 5.

Building Name	**Solar radiation from CEA (kWh/m^2 year)**	**Solar radiation from Carta de Potencial Solar' (kWh/m^2 year)**	**Relative Error (%)**	
			1400 kWh/m^2 year	1600 kWh/m^2 year
B41433	1579.764	1400-1600	12.84	-1.26
B41221	1570.406	1400-1600	12.17	-1.85
B42072	1589.724	1400-1600	13.55	-0.64
B40594	1653.284	> 1600	0	3.33
B41114	1616.269	> 1600	0	1.01
B41927	1543.791	1400-1600	10.27	-3.51
B41237	1595.788	1400-1600	13.98	-0.26
B42226	1735.613	> 1600	0	8.48
B42641	1514.319	1400-1600	0.77	-5.36
B42123	1632.913	1400-1600	0.83	2.05
B42305	1534.118	1400-1600	0.78	-4.11
B41749	1444.973	1400-1600	0.74	-9.68
B42455	1526.723	1400-1600	0.77	-4.58

B42526	1486.979	1400-1600	0.76	-7.06
B42204	1510.651	1400-1600	0.77	-5.58
B42347	1587.611	1400-1600	0.81	-0.77

Table 6 : Results of CEA and Carta de Potencial Solar

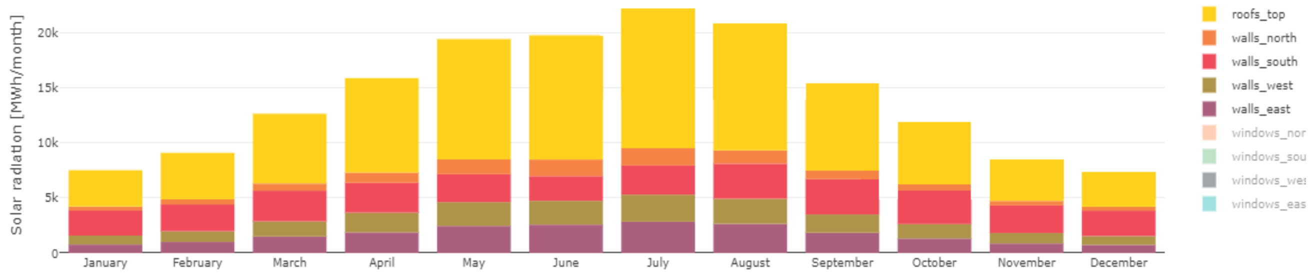


Figure 25: Monthly solar radiation for the Areeiro neighbourhood

CEA also provides the monthly solar radiation in the test region over the course of a year. Similar to the building solar radiation plot the windows are not considered as the effect to the total radiation incident on the building is minimal. Further using solar radiation analysis, a PV electricity potential simulation was conducted the results of which can be found in Figure 26. The results displayed are only for rooftops and southern walls of the buildings in the district.

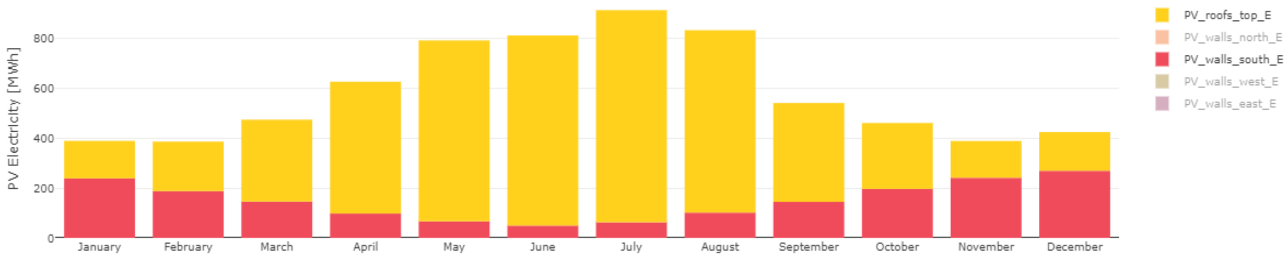


Figure 26: PV panel electric potential of the Areeiro neighbourhood

The results from the simulation are compared against the solar map (Carta de Potencial Solar) developed by the government of Lisbon. The findings of solar radiation per building from CEA are exact values while Carta de Potencial Solar data are presented as a range of radiation values that are further categorized into tiers. As indicated in Table 5, the results of all the buildings from CEA simulation are in conjunction with their prescribed tier in the solar map. There is some degree of overestimation and underestimation present as denoted by the relative error, however, these are less than 9%. Hence, it can be concluded that the CEA values of the building selected for comparison are reliable and corresponds to the correct tier in the Carta de Potencial Solar(Figure 27). All the values of the building selected for comparison accurate resemble the correct tier in the Carta de Potencial Solar(Figure 27). An important fact to note however, is that Carta de Potencial Solar shows multiple tiers on the area of a rooftop, this might be due to how the solar map was developed and as such is able to explicitly identify each square meter of the roof for available solar radiation. While CEA gives a uniform reading over the entire rooftop area of any particular building.

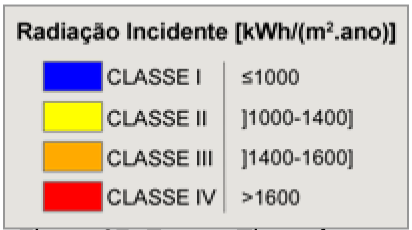


Figure 27: Energy Tiers of Carta de Potencial Solar

The monthly radiation of the region cannot be compared with the same solar map as there is no source for such data in the map. But as it is expected with all the summer months (May, June, July, August), the simulation results (Figure 25) shows these months receive the most solar irradiance. While in the winter the solar radiation on rooftops diminishes significantly.

The PV electric potential (Figure 27) for the region also follows a similar trend to that of the monthly solar radiation, with summertime estimates showing substantially high electricity generation possibility as compared to the winter. However, while the trends on rooftop based PV panels follows the comparable trend to that of the monthly radiation plot during winter. The southern walls of the buildings in the area seem to be able to generate much higher electricity compared to the rooftops during this time. Here again, the data can not be compared to Carta de Potencial Solar, since its mainly designed to show rooftop solar potential of buildings.

4.2 Analysis results of Multiple Regions based on Literature.

From the literature [12] which focused on solar radiation analysis for all of Lisbon by Teresa Santos. In the study, three general regions of the city are further analysed for their suitability of installing a PV system. By estimating the electricity production potential on the rooftops with a PV panel system. The

Figure 29: Study locations from T.Santos's research.

1 – Hospital

2 – School

3 - Cluster of buildings in city centre.

locations include a hospital (Figure 28; 1), school (Figure 28; 2) and a cluster of residential & official buildings in the centre of Lisbon (Figure 28; 3). Further Figure 28 also uses colour bands to denote yearly electricity generation per band. Each colour also representing a quantified range of electricity.

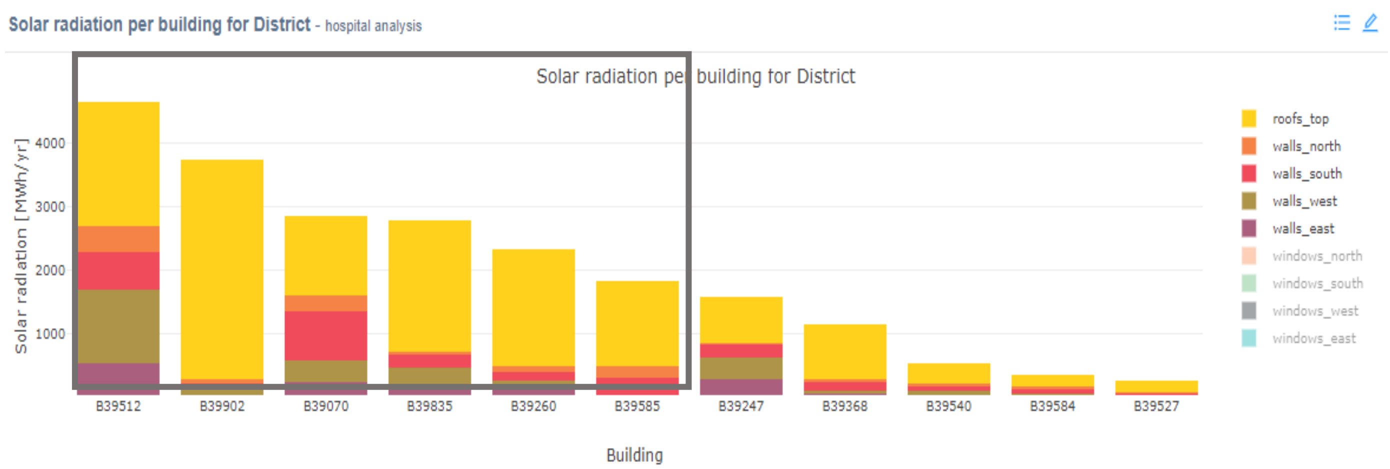


Figure 28: CEA Solar radiation incident on the buildings of the Hospital (27;1)

From the results of the solar radiation of the buildings and comparing each building with that of [12], it is evidently clear that the results from CEA can be trusted. As the rooftops marked in red colour bands (Figure 28; 1) corresponds to building solar radiation on the plot of CEA results since PV electric generation is directly proportional to incident radiation on the building rooftops (buildings inside the grey box in Figure 29). A further assessment of solar PV electric potential results (Figure 30) from CEA seems to back the findings of Figure 29. The yearly average electric potential from photovoltaics is found to be 68.98 Mwh, which fall well within the range of 11.25 - 142.56 Mwh/year denoted by the red colour band in Teresa Santos's study.

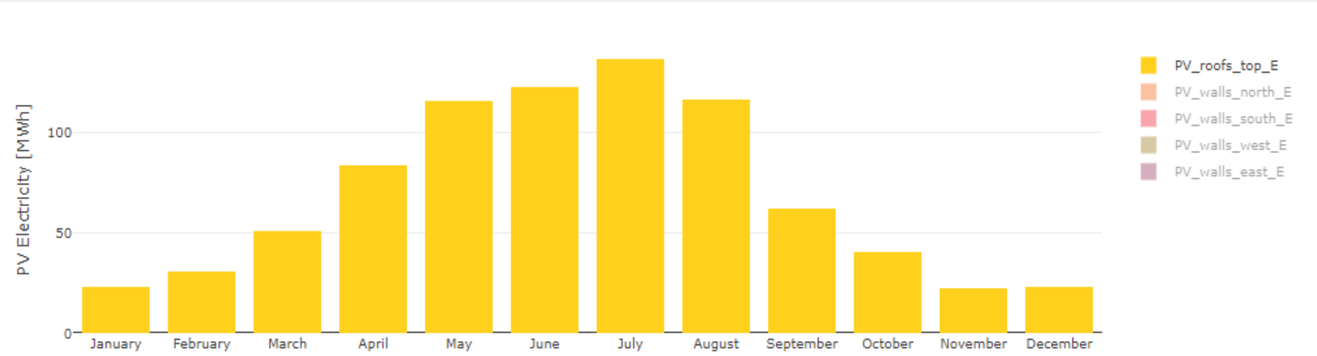


Figure 30: CEA monthly PV electric potential of the Hospital buildings

The next set of results pertains to the school buildings represented in image 2 of Figure 28. Similar to the previous set of results, here too simulation is done on the school buildings with the maximum PV electricity generation. The buildings in consideration are only the main school structures (large red colour band in Figure 28). Here the results also fall within the range denoted by the red band on the literature study. The results this time are fairly towards the lower segment of the range with the annual PV potentials coming in at 22.02 Mwh. However, the main difference lies in how each analysis detected the school buildings. CEA based on its input databases created based on the municipal shapefile seems to identify the buildings much accurately than that of the literature. Figure 33 shows the difference in the building shape detection of CEA, literature and Google Maps. Due to this small miss interpretation of the shape, the results from both the analysis is likely to vary, as the surface area of the building in both will be slightly different. This, in turn, will affect the actual solar insolation on the rooftops which in turn will give varying PV electric potential. How much is the difference in electric potential (although it is expected to be minimal) from both the analysis is hard to quantify as the literature presents its results in a range of values instead of specific numbers.

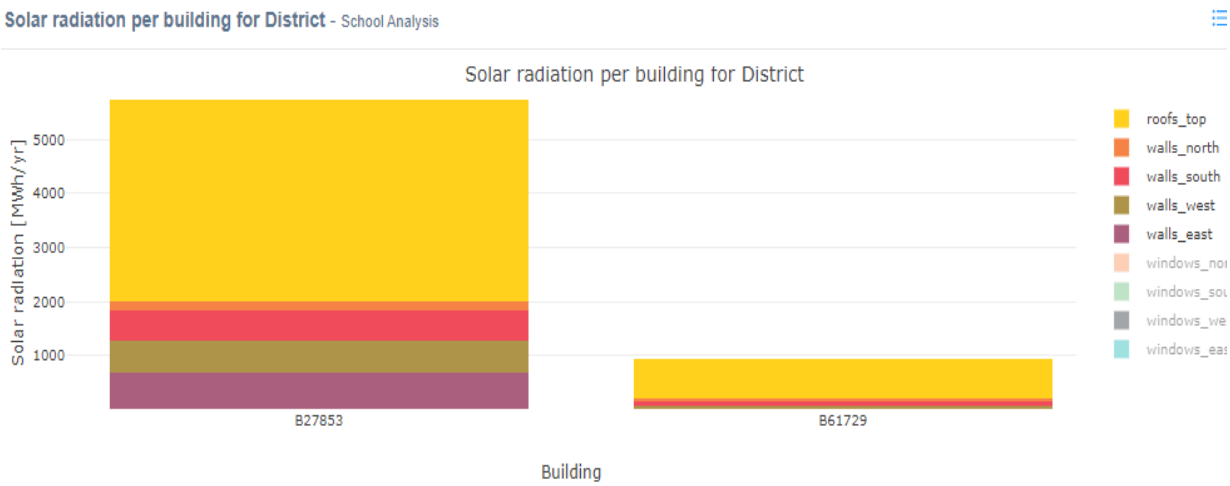


Figure 31: CEA solar radiation incident on top of school buildings.

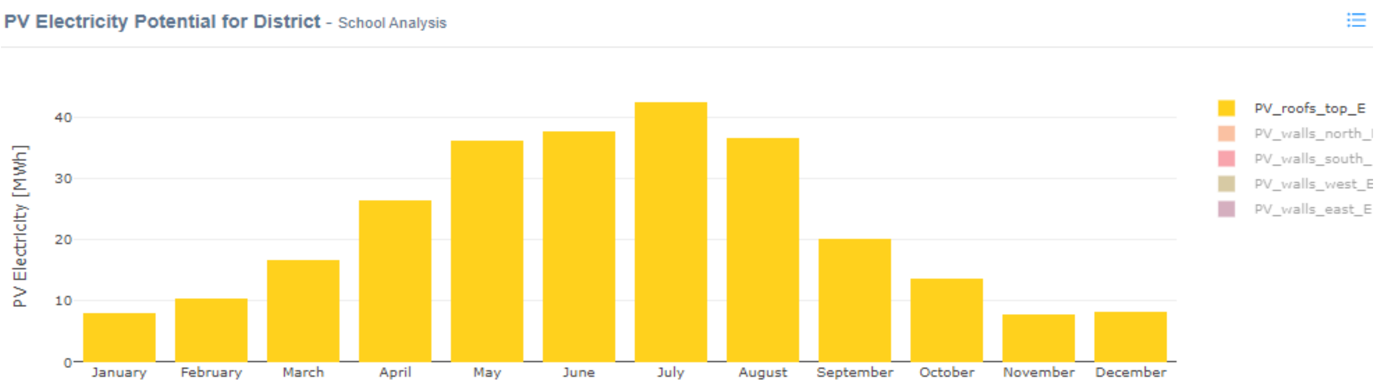


Figure 33: CEA monthly PV electric potential on top of school buildings.

Figure 32: Building shape comparison between CEA (left), Literature (centre) and Google Maps (right).

The final set of results that are discussed concerning the literature is image 3 of Figure 27. The central city cluster of buildings in the city centre Marques de Pombal. In order to obtain the most comprehensive and comparable results, CEA analysis is done on the buildings with rooftops PV electric capacity of 11.25 - 142.56 Mwh/ year (red band; Figure 28).

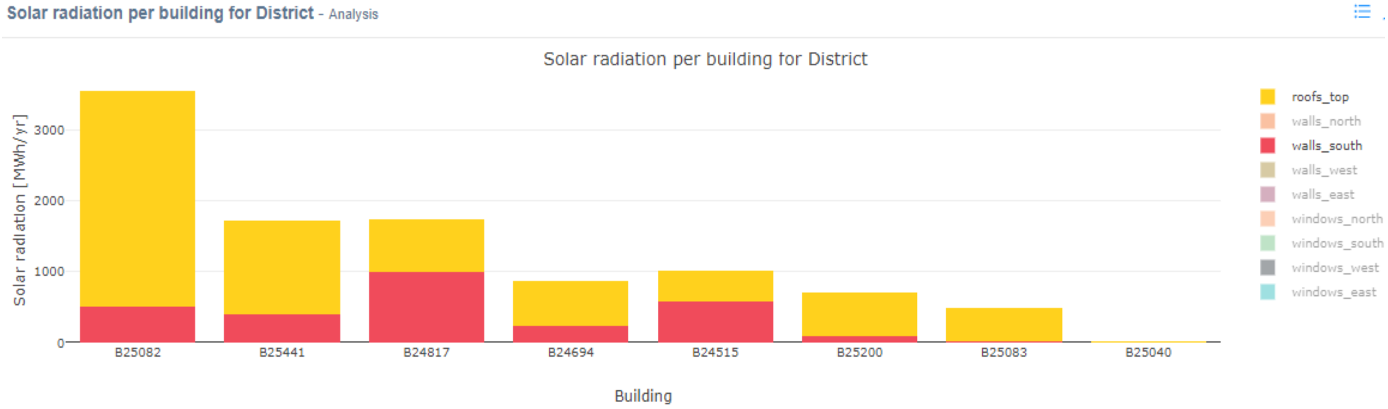


Figure 34: CEA results of solar radiation incident on top of building

As with the two locations hospital and school, the results of solar radiation of the buildings and the average annual PV electric potential of the buildings relate directly to the findings of the literature. The annual average PV electric generation of the buildings is found to be 35.88 Mwh, comparable to the range of the red colour band (Figure 28).

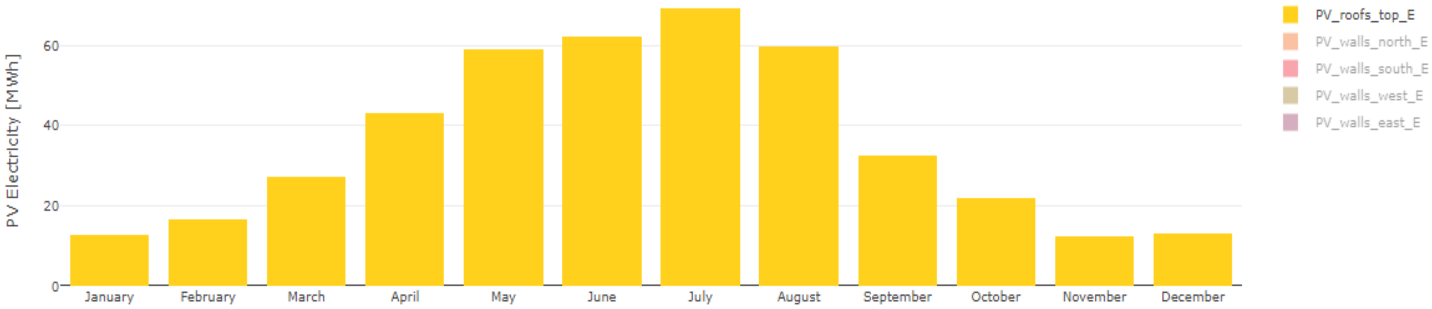


Figure 35: CEA results of PV electric potential on top of building cluster.

There is, however, some discrepancies in same manner as that of the school buildings, here the identification of the buildings in CEA is not accurate. While the literature study was able to correctly map the buildings. This again can be attributed to the municipal shapefile that was used to generate the input files. The results of the simulation conducted through CEA does compliment the study carried out by Teresa Santos et al. However, as with neighbourhood analysis in Areeiro, precise comparisons can not be concluded as both the study presents results in a different structure and the results from the literature of Teresa segments photovoltaic electricity potential in very large range of values. Making it difficult to identify exactly how much each building estimates in the study differ. For comparison, the results are tabulated below.

Building Regions	**School**	**Hospital**	**Marques de Pombal**
Literature results (Mwh/year)	11.25 - 142.58	11.25 - 142.58	11.25 - 142.58
CEA results (Mwh/year)	22.02	68.98	35.88

Table 7: Comparison of CEA results against Literature.

4.3 Analysis results of three buildings located in Oeiras.

The third analysis conducted for three buildings located between the outer suburbs of Lisbon city and Oeiras. These buildings are located between Lisbon and Oeiras region. The data of solar radiation on building rooftops were provided by the municipality of Oeiras, this solar data was produced using a GIS-based application. The results of these three simulations were over the course of an entire year presented in the units W/m^2 for every hour of the day. As such the data had to be converted to the format of CEA outputs for a reasonable comparison.

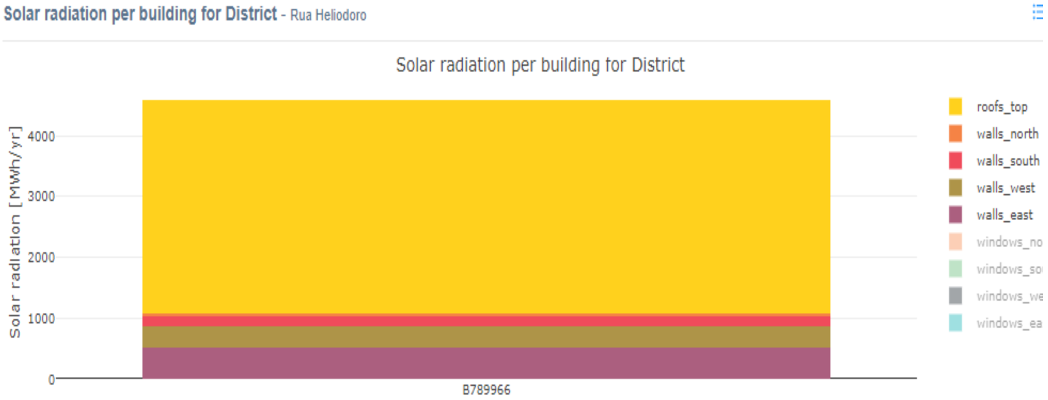


Figure 37:Solar radiation on rooftop building in Rua Heliodoro Salgado,7

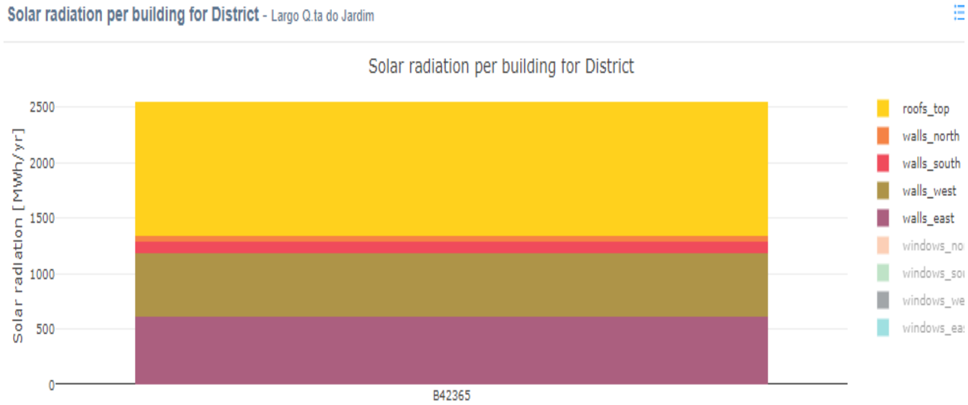


Figure 36:Solar radiation on rooftop building in Largo Q. do Jardim, 1

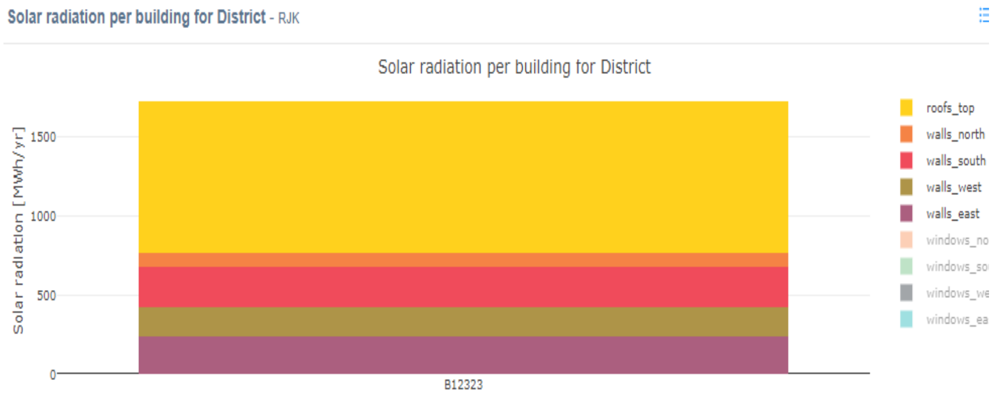


Figure 38:Solar radiation on rooftop building in Rua J Kubitschek de Oliveira , 20

Building Name	Solar radiation from CEA (MWh/year)	Solar radiation from Oeiras Municipal Source (MWh/year)	Relative error (in percentage,%)
Rua Heliodoro Salgado, 7	3497.58	3183.62	9.86
Largo Quinta do Jardim, 1	953.27	1210.3	-21.23
Rua J. Kubitschek de Oliveira, 20	953.27	918.33	3.805

Table 8 : Annual rooftop solar radiation comparison of the Oeiras buildings

Table 7 details the exact values of the solar radiation from the simulation in the City Energy Analyst and compares this information against the data provided by Oeiras Municipality. For two of the buildings, the software seems to overestimate the rooftop incident radiation but this is relatively low; with an error percentage of less than 10%. However, the CEA simulation seems underestimate the radiation on building at Largo Quinta do Jardim by a significant amount (-21.23%). To understand why such large error exists a further analysis was done on the monthly data of solar radiation on the same buildings, as shown in the graphs (Figure 39, 40,41). The results of the monthly solar radiation simulation are

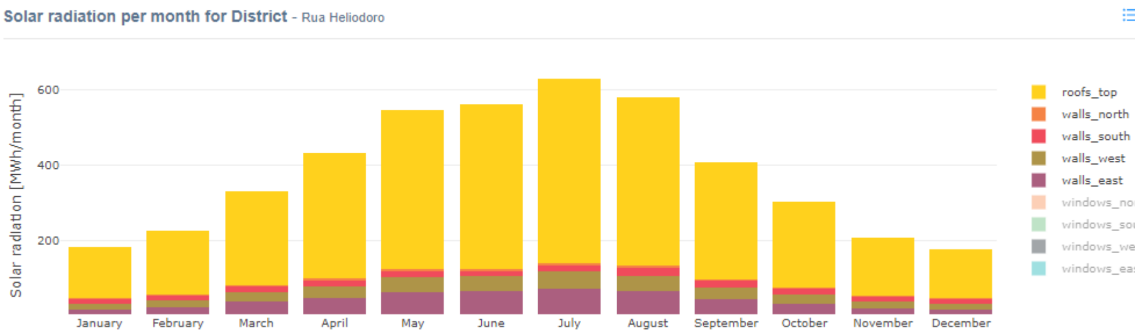


Figure 39:Monthly Solar radiation on rooftop building in Rua Heliodoro Salgado, 7

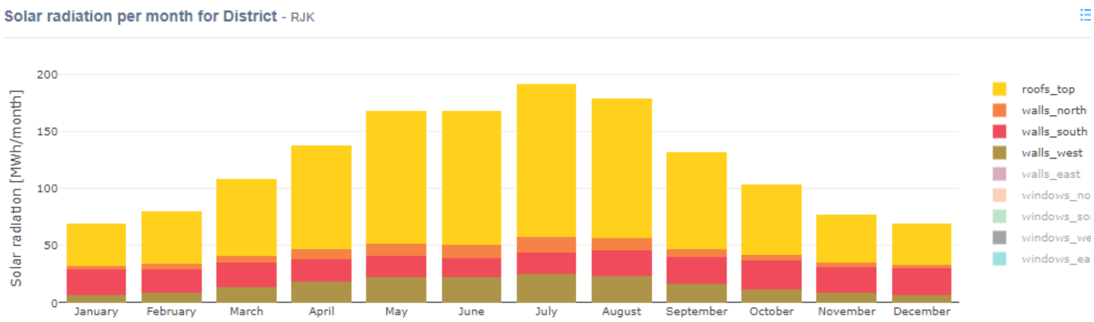


Figure 40:Monthly Solar radiation on rooftop building in Rua J. Kubitschek de Oliveira, 20

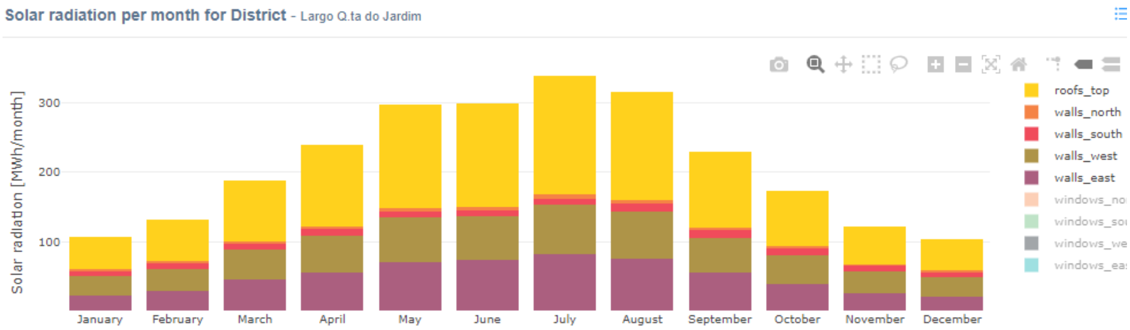


Figure 41:Monthly Solar radiation on rooftop building in Largo Qunita do Jardim, 1

tabulated and plotted for comparison against the data from the Oeiras Municipal resource; as presented in Figure 42.

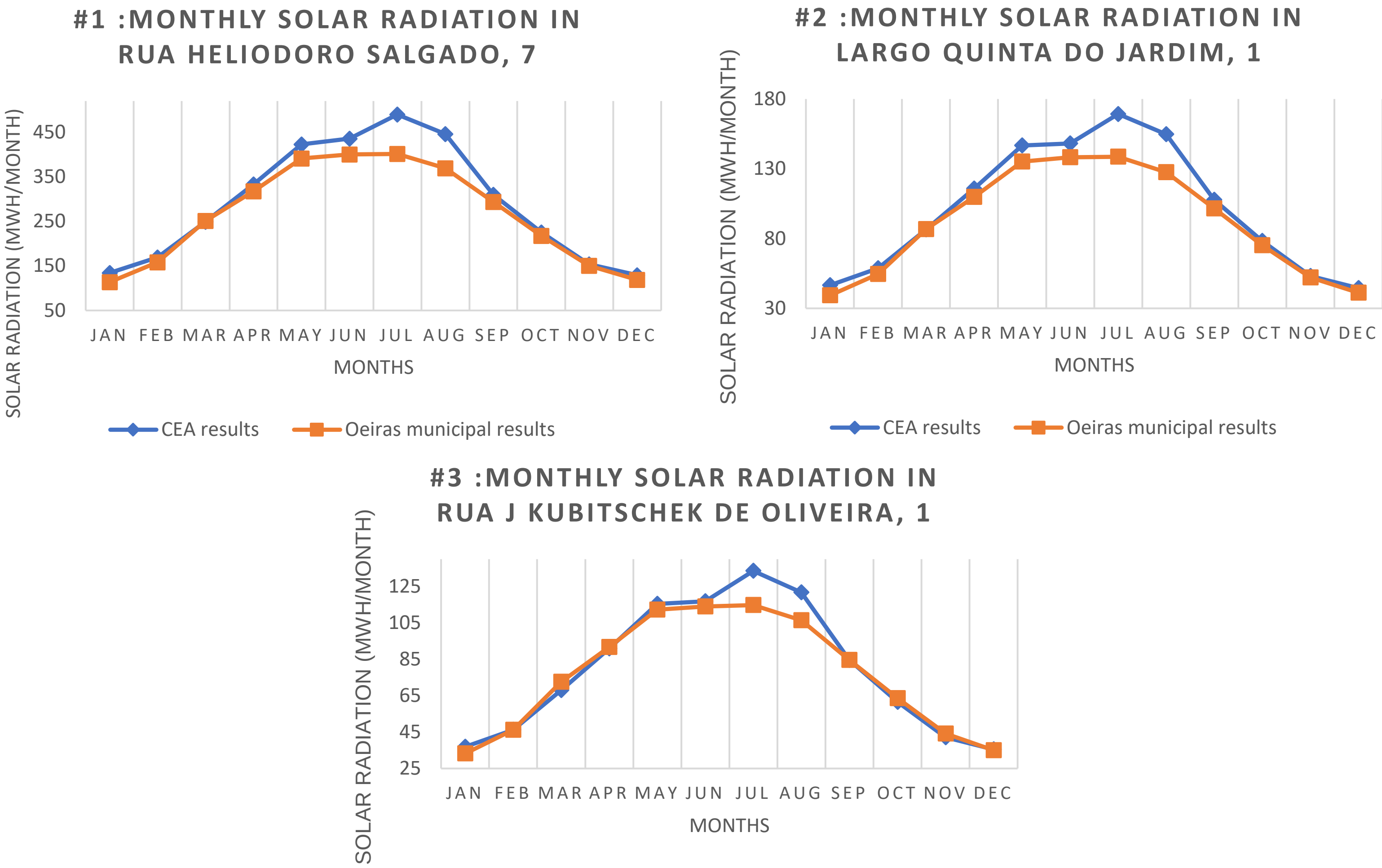


Figure 42: Graphical comparison of the monthly results for the three buildings in Oeiras.

The monthly radiation graphs validate the main regions of over and underestimation that was observed in the annual solar radiation data much more explicitly. Visually it can be noted that the simulation of CEA mainly overestimates the solar radiation during the summer months (May, June, July and August) and in January. Plot #3 is where the CEA seems to underestimate the solar radiation on the rooftops for the month of March. With major deviation from the Municipal data in the month of July. In order to have a closer look at the deviation of the results from one another, the relative error of the monthly solar radiation data for each building is studied in Table 8.

Building Name	**Rua Heliodoro Salgado, 7**	**Largo Quinta do Jardim, 1**	**Rua J Kubitschek de oliveira, 1**
Month	**Relative error (in percentage,%)**		
January	18.29	18.51	11.11
February	6.87	7.46	0.10
March	-0.80	-0.10	-6.36
April	4.8	5.44	-0.89
May	7.96	8.50	2.78
June	8.97	7.26	2.53
July	22.04	22.10	16.34
August	20.81	21.32	14.51

September	5.45	6.12	0.068
October	3.43	3.96	-3.08
November	1.84	2.12	-4.85
December	8.68	8.30	1.36

Table 9 : Relative error between CEA and Oeiras Municipal Datasets

The information revealed on the comparison graphs (Figure 42) is more evident when the relative error of the CEA analysis is evaluated against that of the Oeiras data. Although the general trend of the results follows what is expected; that is a high amount of solar radiation during summertime followed by a much lower quantity in the winter. The difference between the highest and lowest solar radiation from CEA simulation for each building respectively is as follows; 360.37 Mwh (building #1), 124.49 Mwh (building #2) and 97.54 Mwh (building #3). For the Oeiras Municipal data; 287.4 Mwh (building #1), 99.43 Mwh (building #2) and 81.57 Mwh (building #3).

Another important discovery from the comparison is the month during which the lowest solar radiation incidence occurs in both CEA results and Municipal data are different; in CEA simulation results this happens in December while for the Municipal data it occurs in January. The main reason for this can be attributed to how the weather data is utilized in CEA. While the Oeiras solar radiation is mainly for the year 2018, CEA uses the .epw weather format that contains about 20 years of weather data, thus during analysis CEA likely uses a mean value for each month from the vast amount of data, resulting in the difference in the month.

From Table 7, three sets of monthly data are vastly overestimated by CEA compared to the Municipal data and therefore, the relative error for these three months is much higher than desired; error ranging from 11.11% to 22.1%. A reason for such a large margin of inconsistency in the results can be attributed to how CEA creates virtual models of the buildings during analysis to run all the required calculations. CEA models buildings with flat rooftop surfaces, while the buildings at Rua Heliodoro Salgado (building #1) and Largo Quinta do Jardim (building #2) have rooftops that are inclined at angle; Open gable rooftop and Shed rooftop respectively. This variation of the roof surface inclination is not accounted in the CEA input databases, hence such high variation in the results are observed. Moreover, the building situated at Rua J Kubitschek de Oliveira (building #3) has the butterfly variant of the rooftop design, at different minor inclination angles which is why the relative error for this case is comparatively lower in the range of 11.11% to 16.34%, to the other two buildings. In fact this is the main factor that justifies why the rest of the relative error for building #3 is much below $\pm$6.5%. Therefore, even though CEA seems to be making an error when comparing the results, it is, in fact, simulating the building rooftops as flat surface which results in higher solar incident radiation in summer.

The remainder of results for building #1 and #2 seems fairly accurate except for the highlighted months in Table 7(January, July and August); with the relative error within the acceptable range of <9%. While most of the CEA results are overestimates in comparison to the Oeiras data, the software does seem to underestimate solar radiation for building #3 in certain months. Another vital factor that is likely to attribute to the relative errors, is CEA's use of Switzerland building information in constructing the secondary databases. Although this information is supposedly general in terms of European building characteristics, the absence of a default Portuguese database could be attributed to many of the minor deviations between the results.

5 Concluding Remarks

The work detailed in the thesis focused on the utilization of a new open-source urban building energy modelling package, City Energy Analyst(CEA). Primarily to study its solar radiation tool and the accuracy of simulation of solar radiation incident on various regions and buildings of the city of Lisbon. Furthermore, to develop a systematic approach and detailing extensively how to operate the solar radiation modelling aspect of the software. With the abundance of tools and models available online, City Energy Analyst promises to bundle all the vital energy management tools into one software suite.

As per the goal of the study, to understand how CEA operates compared to many conventional and commercial applications. To understand and generate all the primary input databases required to successfully run a simulation on the platform. A comprehensive background study is conducted on how each literature implemented the technique of estimating building heights, as one of the major contributing factors in calculating the incident solar radiation on rooftops. The various studies conducted using LiDAR data reviewed with specific researches of similar nature conducted in Lisbon. These Lisbon based literature reviews formed the basis of evaluating the accuracy of City Energy Analyst.

The results obtained after successful simulation of a neighbourhood in Areeiro, literature-based locations and multiple buildings in Oeiras has shown the aptitude of the software to execute such complex simulations were on par with most of the data used for comparison. The software package is able to produce reliable results though with some minor discrepancies and after verifying its results against the government-based solar map and research data, City Energy Analyst can be deemed dependable in conducting such analysis.

5.1 Limitations of City Energy Analyst.

The main limitation of the software is its reliance on using Swiss building default databases for generating many aspects of the secondary databases that are used in conjunction with the primary input databases to run a simulation. The software segregates its defaults databases into two, where the Swiss data is recommended for analysis in Europe and the Singapore database for countries residing in Southeast Asia. This leads to a generalization of all the buildings in Lisbon as various properties and characteristics of buildings in Portugal are drastically different from that of Switzerland, due to the different climate and weather both regions precede in.

A primary source of unease, which in fact might trouble new users who are lacking in any sort of GIS-related experience is its structure of data handling. The way CEA handles its primary input files and how it strictly demands that users adhere to its systematic approach in input generation for simulation.

The current method of displaying any error while using the software is another of its low points. Since all the errors that occur when running software are displayed in the command prompt window that runs on the background along with the software. Error messages are usually displayed in the form of source code in this window, at times these messages are very difficult to comprehend and pinpoint the source of error. However, the CEA forum the online platform GITHUB allows users to directly report such errors to the developers who respond fairly quickly. This at times feels very impractical to wait for the solution of one of the errors only to find out that certain field in the inputs database was written in lower case letters instead of upper case or one of the attributes in the cells of the database is blank.

It is possible to modify the codes that form the bases of the software since it is open-source. This would enable expert users to model the software with realistic parameters and values related to their location of interest. Yet, it seems to be a difficult feat to achieve since not much information regarding the nature of the program is available. This is true in the case of many of its documentations which convey mainly the exact details of their topic but without any further explanations as to how or why tool needs certain items and databases or how the tool proceeds with the information given to it.

5.2 Future Work.

The work presented here for understanding the software and conduction solar radiations simulations on various regions of the city can be further improved since CEA itself gets updated as frequently as three times a month. In its ever-evolving form, the possibilities of many of its shortcomings as mentioned previously are likely to be revised and improved upon. All the analysis performed in this thesis can be conduct again using actual characteristics and properties of Portuguese builds to obtain much more accurate and reliable results than currently presented. Two of the analysis conducted here (Areeiro and literature) can be further elaborated with the actual data from their source, to quantify the error of the results from CEA simulation. Furthermore, another literature exists which concentrates on solar radiation analysis on building rooftops of the entire parish of Alvalade in Lisbon, CEA simulation can be carried out for this region to further compare the software accuracy.

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