EVALUATING THE SOLAR POTENTIAL OF ROOFTOPS ON CAMPUS SAN JOAQUÍN, SANTIAGO – CHILE USING OPENSOURCE GIS

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Abstract

Over recent years, photovoltaic systems have become increasingly popular for the installation on buildings' rooftops. Due to the increasing demand for electricity through Photovoltaic (PV) systems, it is necessary to evaluate the solar potential on roofs in the first place. Since from these values, it is possible to analyze which rooftops are suitable for the installation of photovoltaic systems to produce the maximum electrical energy but estimate the actual solar potential for applications in the dense urban environment is a difficult mission. In this work, the solar potential in roofs is calculated in Santiago de Chile using opensource GIS. The Global Horizontal Irradiance (GHI) used for this analysis was taken from the Solar Laboratory of Pontificia Universidad Católica de Chile. The other components of radiation: Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) were obtained although of the BRL model for Santiago de Chile. Using the method of Sandia National Laboratory, a typical meteorological year (TMY) was built to handle like input in the process of calculation of the solar potential on the rooftops. A Digital Surface Model (DSM) is used to describe urban geometry. Another sensitivity analysis done in this research was with the albedo, where it was changed in 6 values assuming that exist several buildings with different materials around of building chosen as the case of study. The methodology was validated against measurements made on-site, showing a slight overestimation in the winter months compared to the summer months. An albedo sensitivity analysis was also performed, in which it is evident that the increase of the estimated radiation in the rooftops is linear. Still, the differences in the rise between albedos 0.2 and 0.4 tend to remain constant, therefore, because the compactness effect is relatively meaningless, to use very high albedos.

Keywords: Solar Potential Estimations, GIS, Digital Surface Model, Albedo, Typical Meteorological Year.

1. Introduction

Nowadays, renewable energies are continued growth, as fossil fuels are always more expensive and difficult to find. Furthermore, the latest environmental disasters caused by oil drilling and transportation have further focused the attention of the whole world on the risks connected to fossil fuels. In the last June, the Norilsk diesel oil spill is an ongoing industrial disaster near Norilsk, Krasnoyarsk Krai, Russia. A fuel storage tank at Norilsk-Taimyr Energy's Thermal Power Plant No. 3 (owned by Nornickel) collapsed, inundating local rivers with up to 17,500 tonnes of diesel oil

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(Ilyushina 2020), is a clear example. In the last years, many attempts have been made to control and avoid environmental disaster due to fossil fuels, but it has been in vain. One of the most attractive renewable energy is solar energy. Solar energy is a renewable energy source that can be converted into electrical energy using the Photovoltaics (PV) effect or thermal process. Considering the photovoltaic solar energy conversion, the Building Integrated Photovoltaic systems (BiPV) is an excellent technology for the energy market. In Chile, this field of energy is taking importance because there are optimal conditions in the Atacama Desert. However, in the field of urban environments is just beginning to work.

The complex urban environment with varying building block densities and even more so building elevations, combined with limited available construction data about the existing building stock, are the main reason for the difficulties emerging in the effort to assess solar potential. The solar energy potential of roofs on the urban level has been a significant support of renewable energy strategies action plans on urban or on an even broader level. The rooftops were the first surfaces to explorers when PV decided into an urban environment. However, this process is highly unsuitable for the estimation of solar potential over a broader region with thousands of rooftops. An automated approach is necessary for larger areas. Such methods produce results that are then displayed using a web-based Geographic Information System (GIS) application, which allows users to overview solar potential estimation for their buildings' rooftops (Brumen *et al.* 2014).

However, great efforts are usually made in search of low manufacturing cost by technology research (Socorro García-Cascales *et al.* 2012). To promote the utilization efficiency of solar energy is necessary to evaluate solar energy potential and analyze its distribution over urban areas and satisfy as much urban energy demand as possible (Li *et al.* 2016).

Many authors have worked in solar potential in cities, and they have used diverse methods to estimate de solar radiation in rooftop or facades. (Hachem *et al.* 2011) chose two-story single housing units as case studies to investigate the effects of roof shapes on solar energy potential. Yet these initial studies are often limited to self-shadowing in the built environment. To address the spatial factors, geographic information system (GIS) techniques are also frequently incorporated in the estimation. (Ordóñez *et al.* 2010). Through digital maps produced by Google Earth, they determined the solar potential for the installation of grid-connected photovoltaic systems on rooftops in Andalusia. (Tereci *et al.* 2009) applied LiDAR (Light Detection and Ranging) data to build a Digital Surface Model (DSM), determining the annual solar potential for identified building roofs in combination with ALK map data and GIS software. (Redweik *et al.* 2013) proposed a solar radiation method based on the r.sun radiation model developed by (Suri *et al.* 2007) and incorporated this in the open-source GRASS GIS. The results revealed that the potential of building facades is lower than the roofs, although they usually have large areas.

The objective of this paper is the estimation of the solar potential of rooftops in Campus San Joaquín, Santiago - Chile using opensource GIS, and the incidence of the radiation of albedo in the estimated radiation is analyzed. The first part of the paper present the methodology used with the opensource GIS: QGIS and the SEBE (Solar Energy Building Structures) (Lindberg *et al.* 2015) model although of Complement UMEP from QGIS, including the solar radiation as an input although of TMY built of Sandia National Laboratory (Serpil Yilmaz and Ismail Ekmekci 2017), and the features about Digital Surface Model (DSM) followed by an evaluation of the solar potential of rooftops in Santiago de Chile. Finally, the incidence of radiation of albedo is evaluated.

2. Methodology

2.1. Model

The assessment of the solar potential of rooftops is based on the model of (Lindberg *et al.* 2015), SEBE (Solar Energy on Building Structures), which is in the Urban Multi-scale Environmental Predictor (UMEP) complement of the open-source computer software QGIS.

2.2. Input Data.

The irradiation data used as input in the UMEP complement is a Typical Meteorological Year (TMY). It was built with hourly Global Horizontal Irradiation (GHI) data measured at the solar energy laboratory at the Pontificia Universidad Católica de Chile, San Joaquín campus. The Sandia National Laboratory method (Finkelstein and Schafer 1971) was used for building the TMY.

As well as the geographic location of the area (latitude, longitude, and altitude) and the time zone are obtained from the same Laboratory, whilst the data of the horizontal diffuse irradiance (DHI), the direct normal irradiance (DNI), were obtained through the BRL estimation model (Rojas *et al.* 2019). The digital surface model (DSM) was obtained through photogrammetry with a resolution of 1 m, and a dimension of 280 m x 395 m.

2.3. Typical Meteorological Year (TMY) and Irradiation data.

The Sandia method has been used for constructing the TMYs, which is based upon the Finkelstein-Schafer (FS) statistic for selecting the single month candidates (Finkelstein and Schafer 1971). The FS statistic for a meteorological variable X to be considered in the TMY is defined as,

$$FS_X(y,m) = \frac{1}{N}\sum_{i=1}^{N}\left|CDF_m(X_i) - CDF_{y,m}(X_i)\right| \qquad \text{(eq. 1)}$$

where CDF_m is the long-term cumulative distribution function of daily values of variable X for month m, $CDF_{y,m}$ is the short-term (corresponding to year y) cumulative distribution function of daily values of X, and N is the number of bins. The month candidate is corresponding to the minimum value of the weighted sum (WS) of FS statistics corresponding to each meteorological variable considered.

$$WS(y,m) = \sum_{X=1}^{M} W_X\ FS_X(y,m) \qquad \text{(eq. 2)}$$

Where W_X is the relative weight of the variable X, and M is the number of variables involved.

The data used as input for the analysis is obtained in the following way. In essence, the GHI is derived from the measurements obtained from the solar Laboratory of the Pontificia Universidad Católica de Chile, the rest of the components (DNI and DHI) are obtained from the BRL model of diffuse radiation prediction, applied for Santiago de Chile (Rojas *et al.* 2019). Using the eq. 3:

$$d = \frac{1}{1+e^{-6.274+7.6266k_t-0.0398AST-0.0178\alpha+2.606K_t+2.3392\psi}} \qquad \text{(eq. 3)}$$

Where k_t is hourly clearness index, AST is solar time, α solar altitude angle, K_t daily clearness index, and ψ is persistence.

2.4. Calculation of radiation in rooftops

In Fig. 1 shows the workflow of the calculation of the solar potential of rooftops. Firstly, we have the measured hourly GHI, then the BRL model is applied (García et al. 2017), and the artificial series of DHI and DNI are obtained. After that, the Sandia National Laboratory method is applied to build the TMY. The digital surface model (DSM) is made from photos taken from Google Earth and using the technique of photogrammetry to obtain a three-dimensional model, which in this case will be considered only the roofs of the DSM. Already with this data, we proceed to use the UMEP plug-in of the open-source software QGIS: the SEBE method. In this part of the process, factors such as wall height, wall aspect, the view factor are calculated from the DSM provided, and the value of albedo is introduced. The result of this process is the energy in the rooftops indicated in the MDS; they are superimposed in an OpenStreetMaps template, which coincides with the MDS since it is georeferenced according to the Universal Transversal Mercator (UTM) coordinates of the place under study.

The area of study is Campus San Joaquin, Santiago - Chile can be seen in the map obtained from OpenStreetMaps in Fig. 2. Consequently, the output of this methodology consists of several maps for roofs of total irradiance, annuals, monthly, or daily.

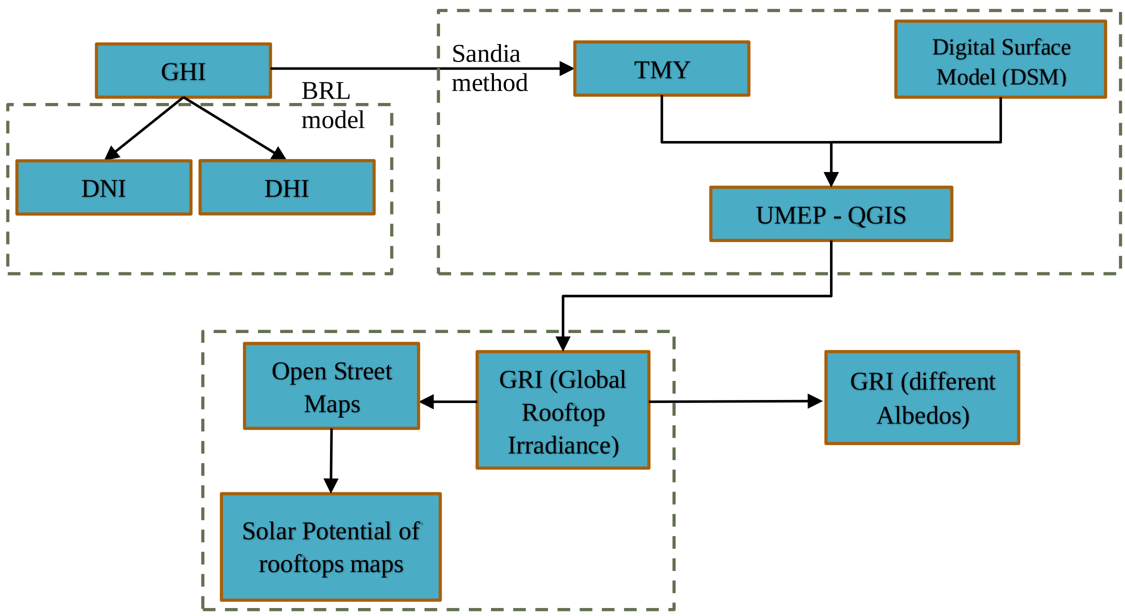

Fig. 1. Methodology to estimate solar potential on Campus San Joaquín, Santiago - Chile

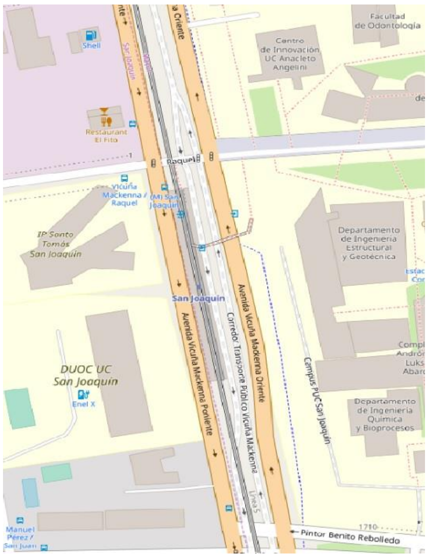

Fig. 2. Map from OpenStreetMaps of Campus San Joaquín, Santiago - Chile

3. Results

The results are shown below in Fig. 3 is the total monthly energy of two characteristic months such as January (summer) and June (winter), on the roofs of buildings on the San Joaquin campus, Santiago - Chile. It can be observed how the radiation on the rooftops tends to be uniform despite the different heights that each building has as well as it is remarkable that the selected urban environment is very open to the field of obstacles. Similarly, due to compacity, we can observe a slight change in the pattern of radiation. Even though not all the buildings were taken into account, it should be noted that the QGIS considers all the buildings, since the MDS has the information of all the heights present in the selected area.

In Fig. 4 shows the annual solar radiation over this study. As expected, this figure clearly illustrates that irradiation levels of building roofs are usually much higher when compared with ground surfaces. The study area is 280 m x 395 m, and the annual total solar energy reaches 1800 kWh/m^2/year. Moreover, this is compared with the global horizontal irradiation measured in Fig. 5, although the differences between estimated and observed values are slightly more than 4% for the first three months, the differences for winter months relatively high, and the average value is 43%.

In general line, we can see an overestimate of the estimated solar potential on the roofs concerning the incident radiation measured. It is due to the overlap of some buildings in others (Brito *et al.* 2019).

a) b)

Fig. 3. Monthly Solar Potential on the rooftops. a) January, b) June

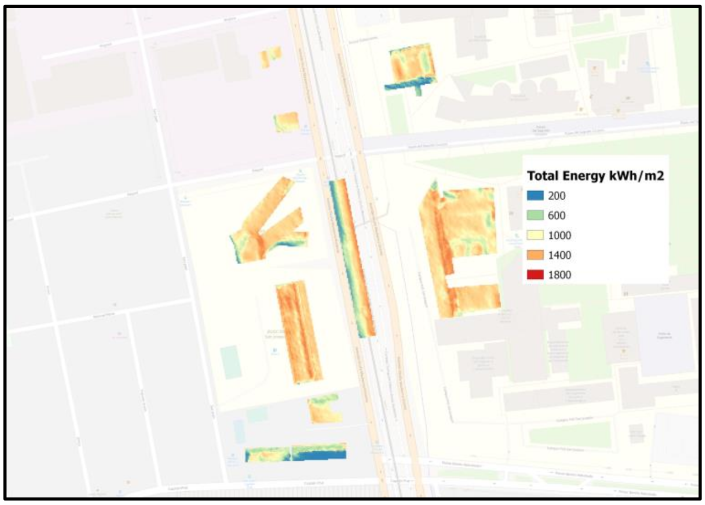

Fig. 4. Annual Solar Potential on Campus San Joaquín, Santiago - Chile

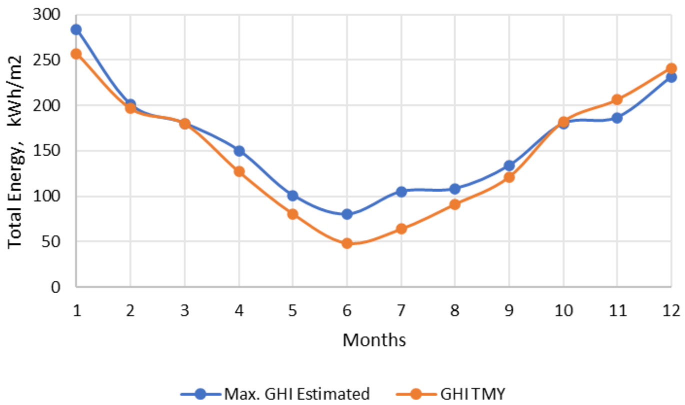

Fig. 5. Comparison GHI from TMY, and GHI on rooftops

Quantifying the graph of Fig. 5, we can see Tab. 1 in which we realize that the average quadratic error is 20 kWh/m^2. This value, in annual energy, does not have a greater incidence, we would be talking about an error of approximately 14%, which is evident in the winter months, but this is due to the effects of shadows by buildings close to each other.

Tab. 1. Metrics Errors for evaluating Solar Potential in rooftops

RMSE	20.9 kWh/m^2
NRMSE	14%

4. Sensitivity analysis of albedo radiation

One of the factors affecting the calculation of radiation in urban environments is reflected radiation, in which the albedo is the main factor, depending on the surfaces surrounding the buildings under study. In the case of roofs, the incidence of albedo only depends on higher buildings with very distinct wall surfaces. To have an idea of the construction materials found in urban environments, Tab. 2 is shown, where the albedo value and the emissivity of each material are also shown.

Tab. 2. The albedos of various materials.

Material	Albedo	Emissivity
Concrete	0.3	0.94
Red Brick	0.3	0.90
Building Brick	-	-
Concrete tiles	-	0.63
Wood (Freshly planed)	0.4	0.90
White paper	0.75	0.95
Tar paper	0.05	0.93
White Plaster	0.93	0.91
Bright galvanized iron	0.35	0.13
Bright aluminium foil	0.85	0.04
White pigment	0.85	0.96
Grey pigment	0.03	0.87
Green pigment	0.73	0.95
White paint on aluminium	0.80	0.91
Black paint on aluminium	0.04	0.88
Aluminium paint	0.80	0.27-0.67

Gravel	0.72	0.28
Sand	0.24	0.76

Surface material with a high albedo index (reflectivity) to solar radiation reduces the amount of energy absorbed through building envelopes and urban structures and keep their surfaces cooler. Materials with high emissivities are good emitters of long-wave energy and readily release the energy that has been absorbed as short-wave radiation (Asimakopoulos *et al.* 2011).

In our case, we used albedo values between 0.1 and 0.6 to exemplify that the buildings were surrounded by other structures that are made of various construction materials that often exist in today's urban environments. In Fig. 6, the behavior of the total radiation is observed as it tends to increase linearly. The differences in the increase of the annual solar potential estimated with albedos between 0.2 and 0.4 trends to be constant. When the albedo tends to be less than 0.2, the radiation no longer experiences any change but remains constant.

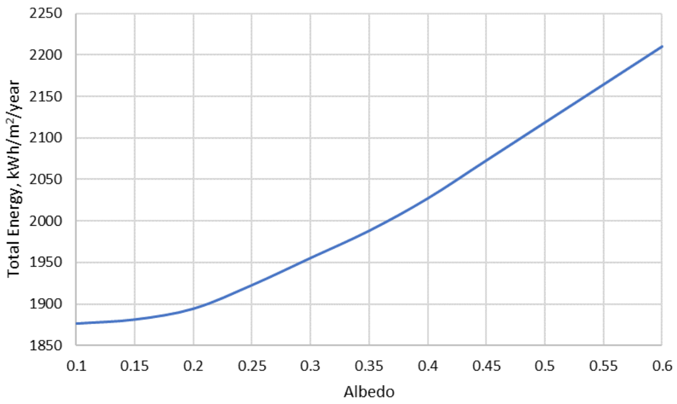

Fig. 6. Solar potential of rooftops with different albedo values

5. Conclusions

In this paper, we have described a methodology for estimating solar potential on roofs through an open-source computer tool QGIS. The Solar Energy on Building Envelopes (SEBE) model for the estimation of short-wave irradiance on roofs is a UMEP add-on to the QGIS computer software. It is classified as a 2.5-dimensional model and makes use of digital surface models to calculate solar radiation. Our digital surface model was obtained through a process called photogrammetry based on satellite photos taken from Google Earth. To get a detailed description of the forcing conditions, the model uses a TMY built through the Sandia National Laboratory methodology using as a basis the measured global horizontal irradiation, diffuse, and direct normal radiation estimated through the BRL model. The methodology was validated against measurements made on-site, showing a slight overestimation in the winter months compared to the summer months. However, this error is mostly due to the effect of compactness of the studied area. An albedo sensitivity analysis was also performed, in which it is evident that the increase of the estimated radiation in the rooftops is linear. Still, the differences in the rise between albedos 0.2 and 0.4 tend to remain constant, therefore, because the compactness effect is relatively meaningless, to use very high albedos.

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