

# Application of GIS tools to the Improvement of Energy Supply in PV Rooftop Installations

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## Abstract

Present work studies the energy supply from photovoltaic (PV) installations in industrial conglomerates using the rooftops as a surface to install the PV panels. The study is based on a modelling procedure that takes into account the specific characteristics of the rooftop, shape, size, azimuth and inclination, using GIS tools to identify these parameters for every single rooftop. Modelling has been developed modifying the tilt angle of the PV panel for vertical and horizontal PV panel layout and analyzing which one of the two configurations generates more energy. The study has been extended for tilt angles from the horizontal plane to the latitude of the location. The methodology uses a previous study in determining the optimum number of PV panels that can be placed on the rooftop. Shading effects have been taken into account for energy supply calculation, resulting in a variation with the tilt angle of the PV panel that depends on the range of the tilt angle; three ranges have been identified, low ( $0 \leq \beta/\phi \leq 0.3$ ), medium ( $0.3 \leq \beta/\phi \leq 0.8$ ) and high ( $0.8 \leq \beta/\phi \leq 1$ ). Maximum variation, 1.6%, has been observed in the low range, while for the high range energy supply does not seem there is no blocking to depend on the tilt angle. The results show that the modelling matches theoretical predictions within accuracy higher than 99.4%. Modelling has also been developed for two different configurations of the PV panel positioning, vertical and horizontal. Tests have been applied to the largest and smallest rooftop; the similar trend in the evolution and the close values of the energy supply with tilt angle proves that the methodology can be applied to any of the industrial building rooftops. The results of the modelling show that there is no much difference between the two configurations; however, horizontal configuration works better for larger areas while vertical one is more suitable for smaller areas. Additional row has been added to the layout provided the shadow is out of rooftop bounds. The increase of the energy is not very relevant, barely 1% for the vertical configuration and 0.2% for the horizontal one.

**Keywords:** GIS tools, photovoltaic installations, PV panels, rooftop, shading effects

## INTRODUCTION

Solar energy has become one of the main solutions to remedy or mitigate the greenhouse gases

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(GHG) effect caused by the use of fossil fuels to generate energy. In year 2014, CO<sub>2</sub> emissions due to the generation of electricity and heating in the world achieved the 49% of the use of fossil fuels [1]. Different studies have demonstrated the capacity of mitigation of this kind of facilities [2]. The continuous growing of PV installations in residential areas as well in commercial centers or industrial facilities make the solar energy a promising alternative to the use of electricity from conventional power plants in these sectors. From 1992 until 2020 the growing has been close to exponential [3–8], and its relevance in the electricity mix today has also growth [9, 10].

Large PV installations like power plants have been traditionally located in open areas, while small installations are mostly placed on rooftops of residential, commercial or industrial buildings. These latter cases represents a low percentage of the electricity generation, but contributes to the reduction of greenhouse gasses emissions in urban areas where their concentration is high or critical [11]; therefore, we can use the rooftops of residential, commercial or industrial buildings for PV installations to mitigate the greenhouse gases effect [12, 13]. The potential of building rooftops is based on its capability of receiving solar radiation in currently useless spaces. Three types of buildings are of interest for this purpose, residential, commercial and industrial buildings. Although energy demand from the residential sector is increasing very rapidly [14], taller buildings, blocking the solar radiation and making useless their rooftop for solar applications, currently surround many residential buildings. On the other hand, residential buildings does not currently provide enough space for PV applications and the available area requires a modelling process to determine the amount of energy supply from a PV installation [15]. Commercial buildings suffer, in many cases, from the same problem, although they are potential candidates if they are located in open areas. Besides, their impact into the climate depends on the amount of energy used for their operation, which is very variable around the world [16]. Industrial conglomerates are of higher interest for PV installations, since they are usually of the same height and are located in open areas where there are no blocking effects to the solar radiation. Moreover, the energy rate in an industrial conglomerate is much higher than in residential areas, since the industry requires larger amount of energy per square meter than any residential area [17]. Previous studies have been developed to optimize the use of PV systems on industrial building rooftops for industrial applications [18].

The use of industrial building rooftops as a free area for PV installation require previous study to determine the characteristics of the buildings, especially its location, shape and size. Unless we have onsite information it is almost impossible to know these characteristics, thus we are forced to use GIS tools. Some studies arise from reviewing the bibliography, but most are devoted to the use of rooftops shadow for PV installations in the residential sector [19].

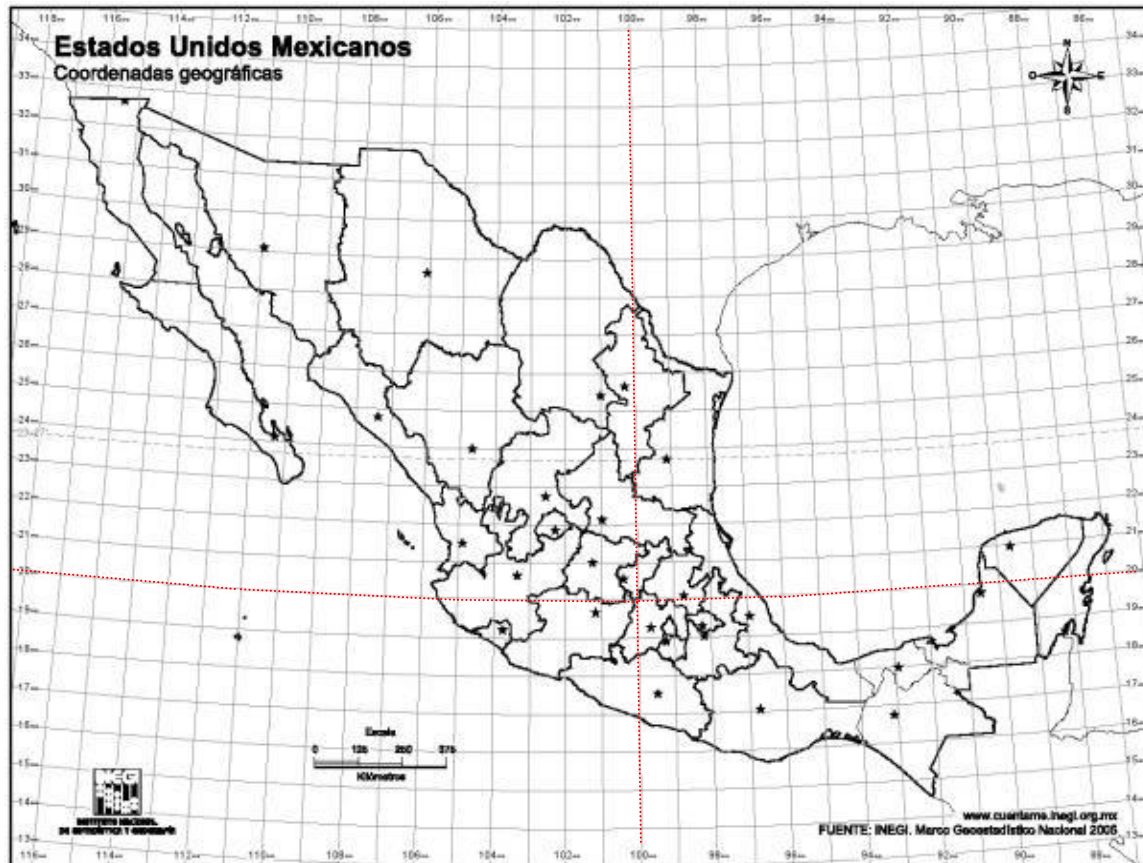
The energy balance of PV installations on building rooftops has been duly modelled [20]. Other studies determine the influence of parameters like the orientation of the PV system on the collected energy, thus on the reduction of the greenhouse effect [21], or include the combined effects of azimuth and tilt angle of the panel [22] basing on the application of the GIS technique. Nevertheless, the misalignment between rooftop surface and PV panel has not been appropriately studied. This situation is important because the number of panels of the rooftop PV installation reduces with the misalignment angle down to a minimum of  $45^\circ$ , then increasing back to the original value [23], thus modifying the energy supply of the PV installation. As a consequence the influence of the variation in the number of PV panels on a rooftop is of great importance to properly determine the energy balance of the PV system.

We have studied an industrial conglomerate of 34 buildings, each one having its own characteristics, shape, size, azimuth and inclination, as for the rooftop is concerned. The industrial conglomerate is located in the city of Toluca (México), where the yearly solar radiation level represents a significant contribution. The use of solar energy in this type of facility is beneficial for the industrial building owner, but also for the electric network, since the increasing energy demand provokes alterations in the energy supply. On the other hand, the use of solar energy in the industrial conglomerate reduces the emissions of carbon dioxide and contributes to preserve the environment.

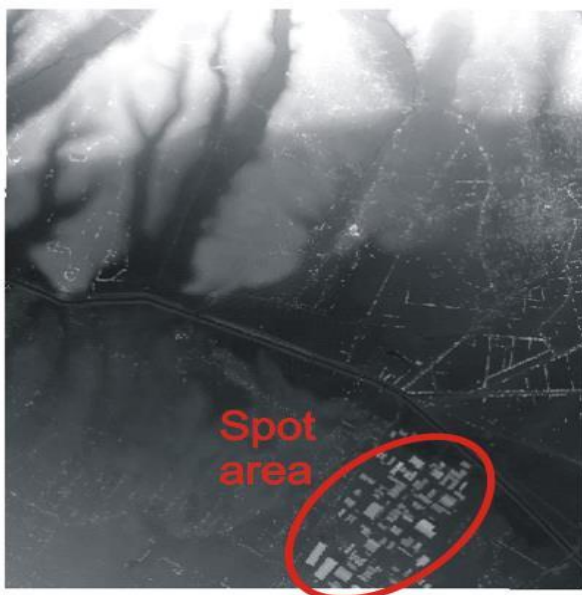
A previous study [23] has been developed in the area to identify the number of PV panels that can be installed on the rooftop of the industrial buildings; this study is used in this paper wherever the results are considered interesting or necessary for the goals of the current work.

## SOLAR RADIATION MODELLING

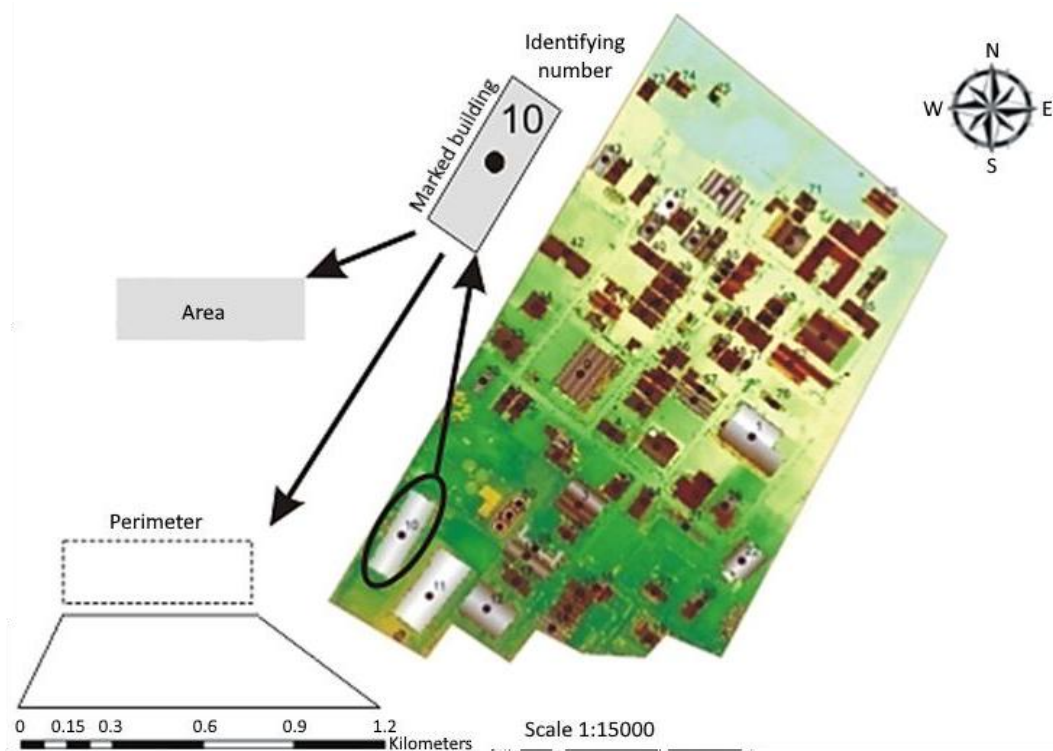
To optimize the collected energy from solar radiation it is necessary a modelling process; this process requires a precise definition of the geographical coordinates of the spot area. In our case, the coordinates are WGS 1984 UTM Zone 14 N [24] with a latitude of  $19^{\circ}26' N$  and  $99^{\circ}39' W$  (Figure 1). The LIDAR images required for our study were taken applying the ArcMap tool shown in Figure 2 [25].



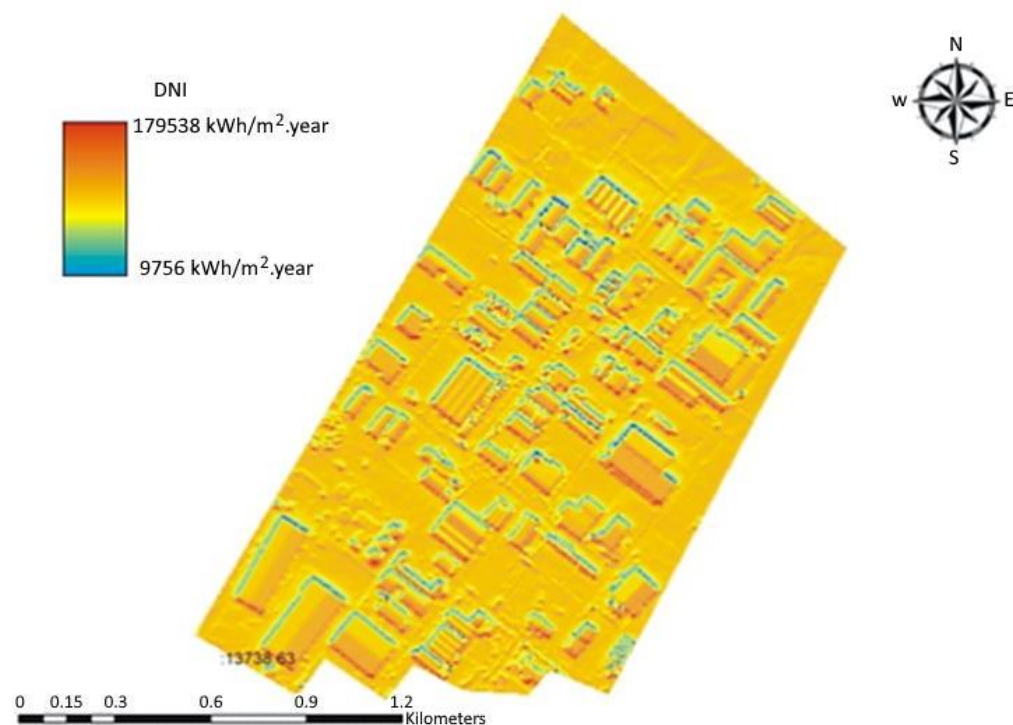
**Figure 1.** Location of the spot



**Figure 2.** LIDAR image of the spot area

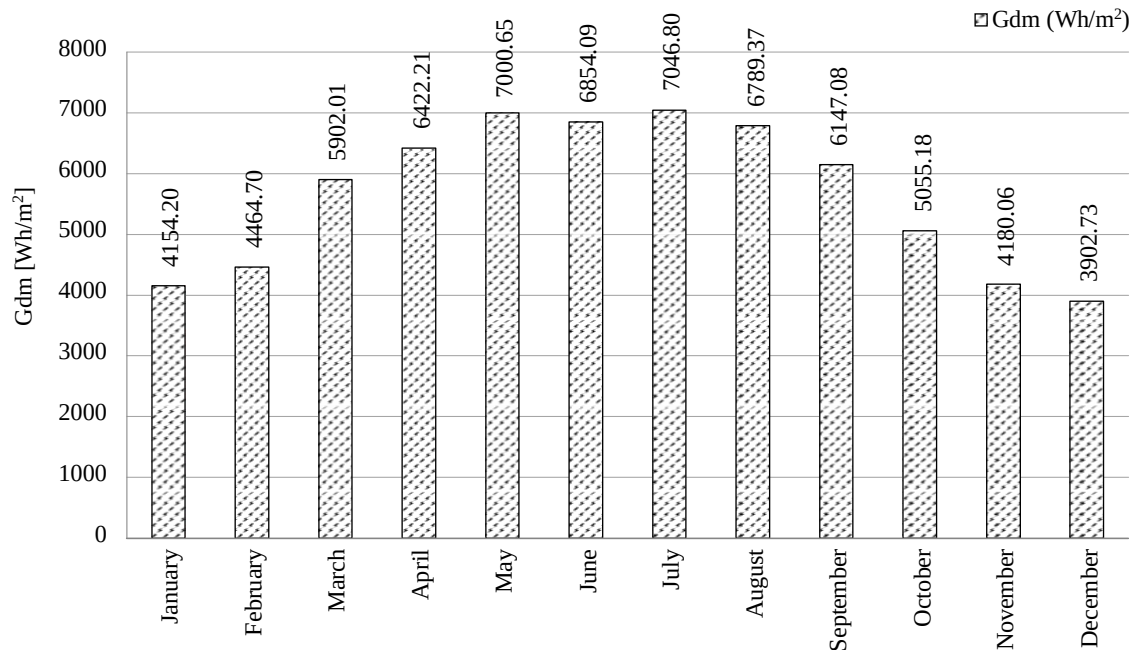


**Figure 3.** Configuration of the industrial conglomerate



**Figure 4.** Yearly average direct solar radiation on the spot area

To properly characterize the industrial conglomerate we have obtained from the LIDAR image a graph distribution of the industries of the conglomerate (Figure 3); this image shows the shape of every industry, its size at a reduced scale and the orientation. The configuration has been obtained using GIS tools to the spot area [26].



**Figure 5.** Monthly average daily irradiance on the spot area

The prediction of the solar radiation onto the spot area has been determined using the GIS tool –Solar Area for a spatial resolution of 5 m × 5 m per pixel. The diffuse solar radiation coefficient has been obtained averaging data for a period of 22 years, resulting in a value of 0.24, which is close to the standard value for clear sky days ( $K_D=0.2$ ). The clear sky index is  $K_T=0.57$ , is also in the range,  $K_T=0.5$  for clear sky days and  $0.6 < K_T < 0.7$  for very clear sky days [27]. Figure 4 shows the Direct Normal Irradiance (DNI) obtained from the application of the GIS –Solar Area tool to the spot area. A more precise details of the DNI values have been represented in Figure 5.

### Solar energy calculation

The implementation of PV systems to replace the use of fossil fuels as energy source requires a precise determination of the solar power generation for the specific spot area [28].

Yearly average daily power generation can be obtained from the equation 1 [29]:

$$E_{d,a} = A_{PV} \eta_{PV} \sum_d I_g^d \quad (1)$$

Where  $A_{PV}$  is the area of the PV panels,  $\eta_{PV}$  the efficiency of the photovoltaic conversion, and  $I_g^d$  the yearly average hourly irradiance.

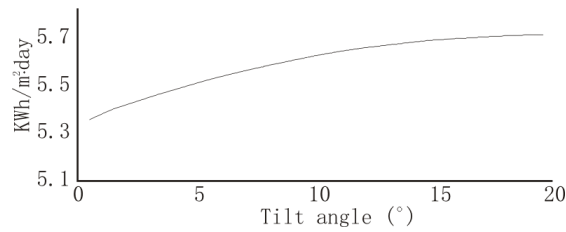
Solar radiation onto a surface depends on the angle of incidence, which depends on the Sun position and tilt and orientation of the surface. For a maximum yearly collection of the solar radiation the optimum tilt is related to the latitude of the location through the equation [30]:

$$\beta_{opt} = 3.7 + 0.6\phi \quad (2)$$

Where  $\phi$  represents the latitude of the location.

Tilted plane receives more energy than horizontal one, but generates a shading effect that may interfere the solar radiation onto the surface placed right behind; therefore, it is required to keep a distance between two rows of PV panels to avoid shading effects.

An additional effect is due to the orientation of the surface, which is caused by the relative position of the rooftop where the PV panel is placed on. In such conditions, solar radiation is defined as [31]:



**Figure 6.** Yearly average daily solar energy

$$I_{\beta,\gamma} = I [\cos \alpha \sin \beta \cos(\psi - \gamma) + \sin \alpha \cos \beta] \quad (3)$$

Where  $\alpha$  is the incidence angle of the solar radiation onto a horizontal plane,  $\beta$  is the tilt angle,  $\gamma$  is the azimuth of the surface, and  $\psi$  is the azimuth of the N-S hemisphere of the surface location, with  $\psi=0^\circ$  for a surface in the North hemisphere facing South, and  $\psi=180^\circ$  for a surface in the South hemisphere facing North.

Figure 6 shows the yearly average solar radiation onto a tilted plane for the location of our study. An optimum tilt angle of  $17^\circ$  has been considered for calculations.

Solar energy evolves with time along the day; therefore, it is a current practice, in PV industry, to use the “Peak Solar Hours” coefficient, which can be obtained from the expression:

$$PSH = \frac{\int_{day} I(t) dt}{1000} \quad (4)$$

Using this coefficient the daily solar energy supplied by a PV panel can be easily obtained from:

$$\xi = I_{\max} PSH \quad (5)$$

### PV layout

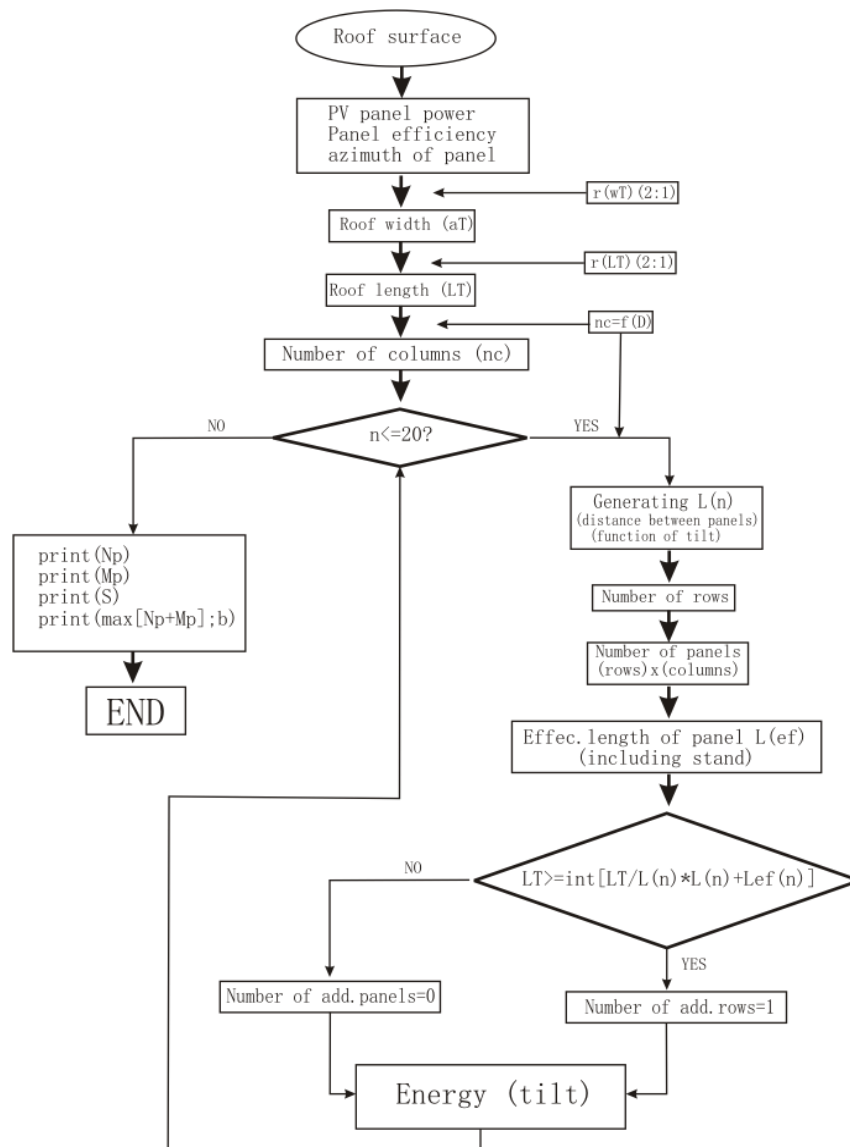
PV layout has been studied and modelled in a previous study [23]. The modelling developed in the reference paper gives the optimum number of PV panels that fit on the rooftop area for the operating conditions, angle of incidence of the solar radiation and shape, size and tilt angle of the rooftop and of the PV panel.

Using data from this modelling we can obtain the collected energy of the PV layout for every industrial building rooftop. The process has been developed using a Python program [32], whose flow chart is represented in Figure 7.

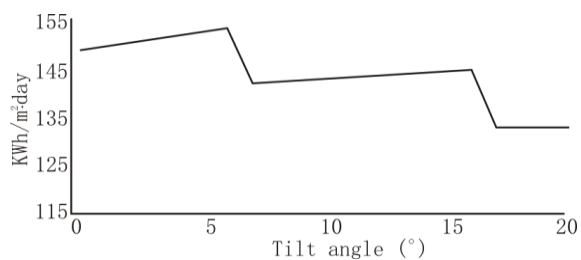
The modelling has been developed for a rooftop initially facing south, modifying the orientation from East to West in steps of  $5^\circ$ . The tilt of the panel has been modified in steps of  $1^\circ$  from an initial value of  $0^\circ$  up to a maximum of  $20^\circ$ , which is a common range for the selected latitude. The surface of the rooftop has been established in  $200 \text{ m}^2$ , a value that matches with the average of the industrial building conglomerate used as reference. Figure 8 shows the results of the calculation of energy with the Python program.

Figure 8 shows the evolution of the supplied energy by the set of PV panels; three different ranges emerge from the observation of the figure; first range, with tilt angle from  $0^\circ$  to  $6^\circ$ , second range, with tilt angles from  $7^\circ$  and  $16^\circ$ , and third range with tilt angles from  $17^\circ$  to  $20^\circ$ .

Energy supply by the PV set shows an increasing linear evolution in the first two ranges, while for the third range it seems to keep constant. The energy supply values and the slope of the range are indicated in Table 1.



**Figure 7.** Flow chart of the Python program.



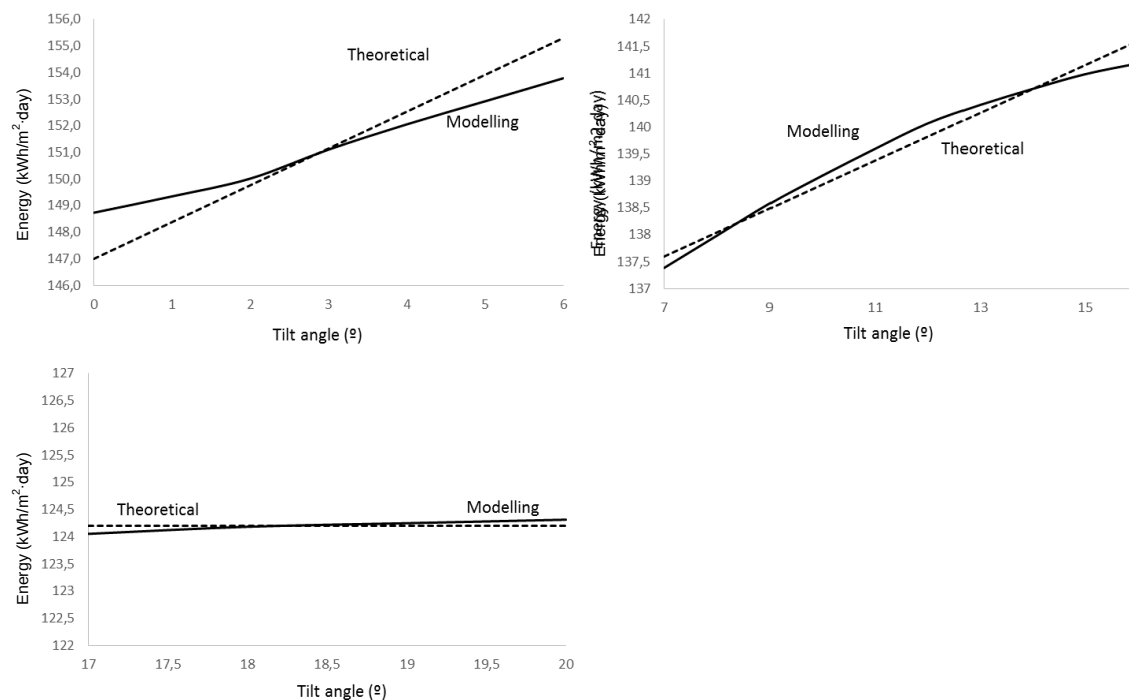
**Figure 8.** Energy supply for a reference surface.

**Table 1.** Energy supply of the PV set

|                                         |      | Tilt angle range |        |         |
|-----------------------------------------|------|------------------|--------|---------|
|                                         |      | 0°–6°            | 7°–16° | 17°–20° |
| Energy supply (kWh/m <sup>2</sup> ·day) | Max. | 155.3            | 141.6  | 124.2   |
|                                         | Min. | 147.0            | 137.6  | 124.2   |
| Slope                                   |      | 1.383            | 0.444  | 0       |

**Table 2.** Variation of number of PV panels with tilt angle

|             |     |     |     |     |     |     |     |     |     |     |     |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $\beta$ (°) | 0   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
| $N_p$       | 188 | 189 | 190 | 190 | 191 | 191 | 192 | 169 | 169 | 169 | 169 |
| $\beta$ (°) | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  |     |
| $N_p$       | 169 | 169 | 169 | 169 | 169 | 169 | 148 | 148 | 148 | 148 |     |

**Figure 9.** Energy supply by the PV set (theoretical and modelling)

It seems that the results obtained in the calculation are not consistent with the ones shown in Figure 6 for the daily energy from solar radiation, which shows an increasing trend with tilt angle in the whole range. The reason of this apparent inconsistency is the reduction of the number of panels because of the increasing shading effect with the raise of tilt angle. Table 2 indicates the variation of the number of PV panels with the tilt angle obtained from the modelling.

We observe the number of panels given by the modelling process remains unaltered for the second and third range, with a constant value of 169 and 148. However, for the first range, there is a variation in the prediction of the modelling for the number of PV panels, increasing with the tilt angle. Despite the variation is not significant, less than 0.6% on average, the variation shows the prediction is not as accurate for the low range of tilt angle, 0° to 6°, as for the other two ranges, where maximum deviation is 0.12% and 0.07%.

Since the number of PV panels cannot be variable within a specific range, we have taken the average value of the interval as representative of the whole range; therefore, we have considered 190 panels for the first range, 169 for the second, and 148 for the third. This consideration, however, generates a deviation in the estimation of collected energy from solar radiation. Taking into account the reference values for every interval, we obtain the following results (Figure 9).

Adjusting the obtained curves for the different ranges of the PV panel tilt angle, we have the following algorithms that reproduce the evolution of the energy supply of the PV set,  $th$  for theoretical prediction and  $m$  for modelling:

a) First range  $0^\circ \leq \beta \leq 6^\circ$

$$\xi_1(th) = 1.383\beta + 147 \quad R^2 = 1$$

$$\xi_1(m) = 0.8698\beta + 148.53 \quad R^2 = 0.9946 \quad (6a)$$

b) Second range  $7^\circ \leq \beta \leq 16^\circ$

$$\xi_1(th) = 0.444\beta + 134.49 \quad R^2 = 1$$

$$\xi_1(m) = 0.4261\beta + 134.7 \quad R^2 = 0.9747$$

$$\xi_1(m) = 4.733 \ln \beta + 128.19 \quad R^2 = 0.9971 \quad (6b)$$

c) Third range  $17^\circ \leq \beta \leq 20^\circ$

$$\xi_1(th) = 4 \times 10^{-13} \beta + 124.2 \quad R^2 = 1$$

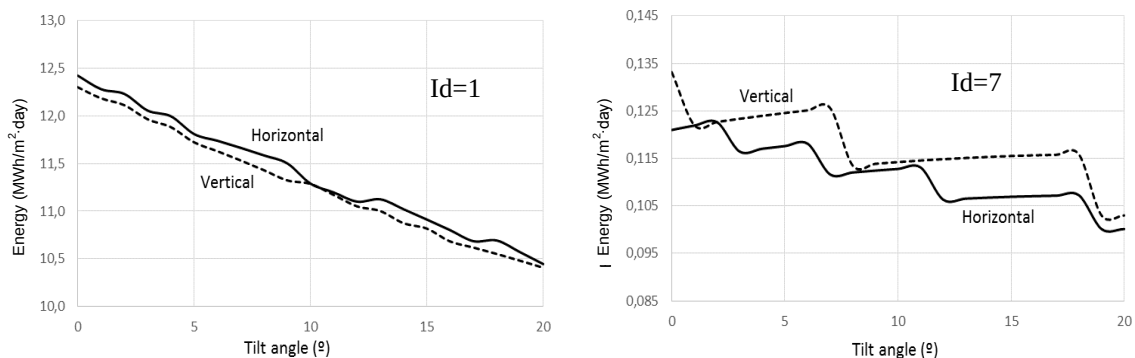
$$\xi_1(m) = 0.0849\beta + 122.63 \quad R^2 = 0.9657$$

$$\xi_1(m) = -0.0163\beta^2 + 0.6893\beta + 117.06 \quad R^2 = 0.9943 \quad (6c)$$

Theoretical prediction, as expected, follows a right line with an accuracy of 100% ( $R^2=1$ ). If we adjust the modelling prediction to a right line, as in theoretical case, the accuracy is not as high, working good for the lowest range of the tilt angle, within a 99.5% accuracy, but not as good for the other two ranges, with accuracies around 97%. Trying to improve the accuracy of the modelling prediction for these two ranges we have adjusted the modelling prediction to a logarithmic and to a second degree polynomial curve for the second and third range, improving the accuracy in the prediction to more than 99.5%. The high results in the accuracy value of the modelling prediction has validated the methodology.

Since the PV panels can be installed in vertical or horizontal configuration, which does not produce identical results in the number of panels [23], we have applied the same methodology to vertical and horizontal configurations. From the 34 identified different buildings, to avoid a very extensive study that is time consuming, we have considered for the analysis the larger and smaller of the 34 buildings, in order to determine if the prediction for the vertical and horizontal configuration shows a significant difference. If the prediction for both configurations shows regular trend with matching results within high accuracy, we estimate the rest of the industrial building rooftops follows the same behavior, thus the methodology is validated and can be applied to any of the rooftops.

The results for the PV layout with vertical and horizontal configuration have been obtained for the two selected industrial buildings, identified as Id=1 and Id=75, representing the maximum and minimum of the rooftop area. These results are shown in Figure 10.



**Figure 10.** Energy supply for a PV layout with vertical and horizontal configuration

We can observe the horizontal configuration of the PV panels layout produces higher energy for the case  $Id=1$  that corresponds to a very large industrial building rooftop area, while for the  $Id=75$  where the rooftop area is very small, the vertical configuration is better. This indicates the horizontal configuration of the PV panel layout fits better in large areas, while for small ones the vertical configuration is more suitable. The difference in the supplied energy between the horizontal and vertical configuration is due to the number of panels of the layout, since one of the configurations fits better than the other to the selected surface, what affects to the number of panels that can take place[23].

It can also be observed that the maximum energy supply corresponds to an angle of  $0^\circ$ , no matter which case is dealt; this is a consequence of the shading effect of the tilted panels that increases with the tilt angle, thus reducing the number of installed panels and the energy supply. The effect is more evident in large areas,  $Id=1$ , where the number of panels is higher and the relative influence of the shading effect increases.

To optimize the layout of the PV installation we have considered the situation in which additional panels can be installed if the shadow they produce is out of the rooftop's bounds. This situation can be mathematically established using the following condition:

$$L_{roof} \geq N_p D + L_z \quad (7)$$

Where  $L_{roof}$  is the length of the rooftop,  $N_p$  the number of panels,  $D$  the distance between two consecutive panels, given by the equation (8), and  $L_z$  the projection of the panel length onto the horizontal plane.

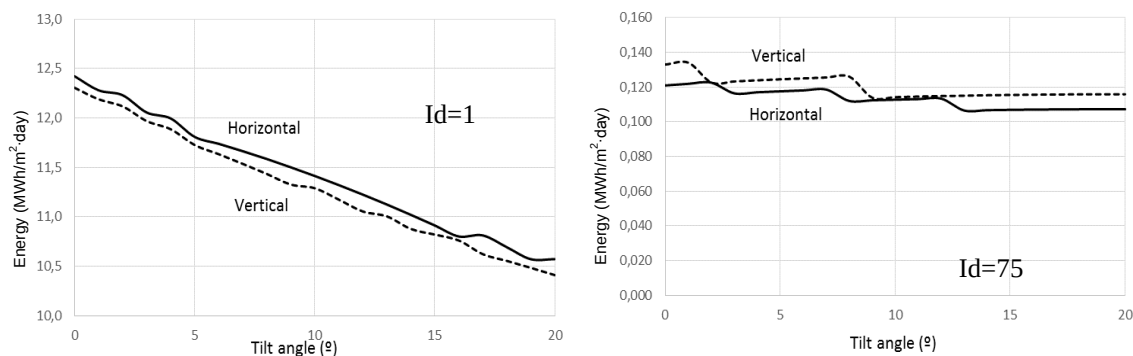
$$D = L_{PV} \left[ \frac{\sin \beta}{\tan(90 - \phi - 23.5) + \cos \beta} \right] \quad (8)$$

$L_{PV}$  is the length of the PV panel,  $\beta$  the tilt angle, and  $\phi$  the latitude of the location.

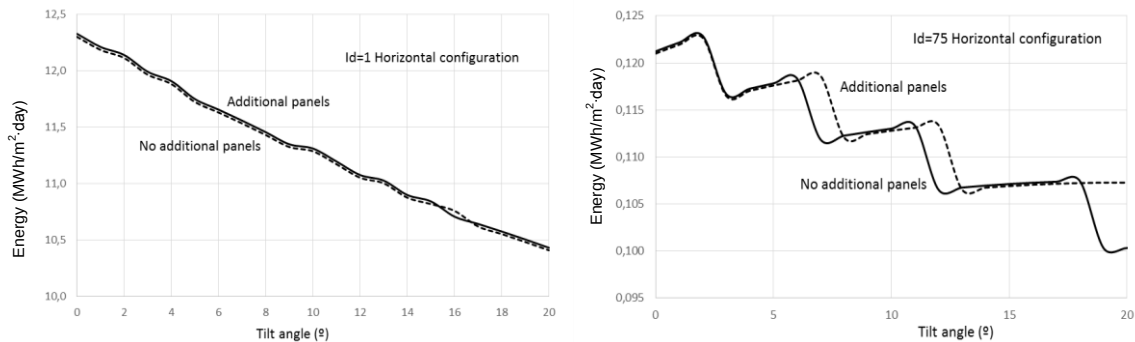
The condition imposed by equation (7) increases the number of panels of the layout, thus the energy collected and generated. The results of applying this condition can be seen in Figure 11.

As in the previous case, without additional panels, the maximum energy input is achieved for an angle of  $0^\circ$ , since the addition of extra panels does not prevent the influence of the shading effect, but rather reinforces it. Likewise, the effect is more relevant for large areas,  $Id = 1$ , a consequence of the influence of greater number of installed panels.

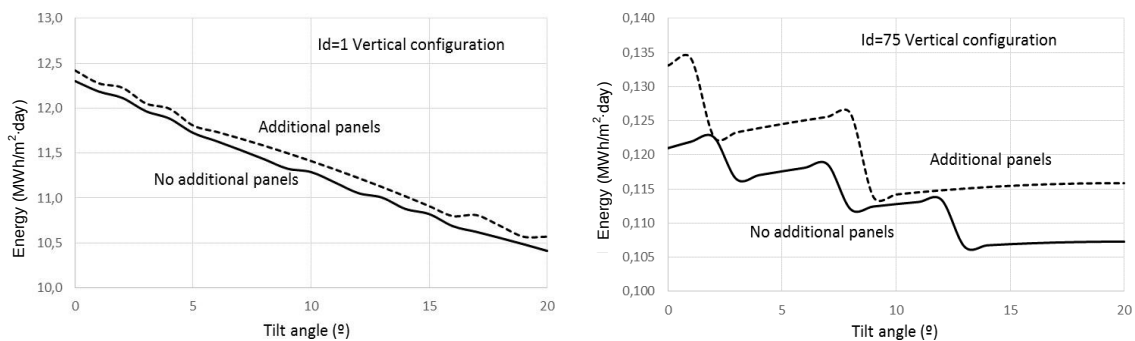
It can be observed the behavior of the PV layout with additional panels is very similar to the one with no additional panels; for very large areas, like in the case of industrial building  $Id=1$ , the horizontal configuration shows higher energy supply than vertical, while for very small areas, such in the case of the industrial building  $Id=75$ , the vertical configuration supplies higher energy.



**Figure 11.** Energy supply for a PV layout with vertical and horizontal configuration with additional panels



**Figure 12.** Energy supply for a PV layout with horizontal configuration with and without additional panels



**Figure 13.** Energy supply for a PV layout with vertical configuration with and without additional panels

Comparing results from both situations, we notice there is a slight increase in the energy supply when the configuration includes additional panels, which is consequent with the fact that the additional panels provide extra energy; however, the difference is not very noticeable because of the low number of additional panels. The difference between the two layouts is shown in Figures 12 and 13.

The analysis of results shown in Figures 12 and 13 indicates the addition of extra panels improve, as expected, the supplied energy for the two represented cases. The other cases have shown a similar behavior with increasing energy supply with the additional panels. Therefore, we can conclude this new configuration provides improving results and is compatible with the layout of the PV installation.

## CONCLUSIONS

A model to determine the energy supply by PV layout on top of industrial building roofs has been developed. The model predicts the energy within high accuracy, 99.4%. The model takes into account the optimum number of panels that can be installed on the rooftop, which depends on shape and size of the rooftop and PV panel as well as on tilt angle of the PV panel and azimuth of the rooftop surface. Energy supply results from the modelling have been compared to theoretical ones, showing a very good matching, within accuracy higher than 99.4%. Two configurations of PV panel layout have been tested, vertical and horizontal; vertical configuration seems to work better for smaller areas while horizontal does for larger ones. Differences in energy supply between configurations are of low significance, 1% for vertical and 0.2% for horizontal. Additional rows have been added to the layout provided the shadow is out of rooftop bounds; the energy improvement has been estimated by 1%.

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