

Rooftop Layout Optimization for PV Installation using GIS

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Abstract

In this work, we develop a new modelling process to optimize the PV installation layout on industrial building rooftops; the model searches for maximizing the number of installed PV panels in a defined spot area, characterized by its shape, size, tilt and orientation. The study focuses on areas of latitude between tropics, but is useful for other latitudes. The method is applied to an industrial conglomerate of reference, made up of 34 industries, whose geographical characteristics have been provided by the GIS technique. The proposed model reduces the area of the spot to a very small size (5m x 5m), thanks to the use of the GIS tools, thus increasing the precision of results and making the solution more reliable. The accuracy of the method is over 98.5%. The model takes into account not only the shape and size of the PV panel but also the tilt angle. The model predicts the number of panels as a function of the tilt angle of the panel and the azimuth of the rooftop. The modelling process has allowed obtaining the surface coverage factor of the PV layout for panels facing to the Equator in rooftops with a specific azimuth. The results of the modelling shows that coverage factor increases with the rooftop's azimuth, having a minimum value of 75% for a rooftop azimuth of 45° and a maximum of 92% for angles of 5° and 85°.

Keywords: Coverage factor, GIS technique, PV panels, rooftop

INTRODUCTION

In year 2015, the global balance of carbon emissions to the atmosphere from industries was of 9.9 ± 0.5 GtC, based on data provided by the involved countries [1]. In 2014, the CO₂ emissions due to heat and electricity generation were the 49% of the global use of fuels around the world [2].

Solar energy is a remedy to the problem of carbon emissions replacing the fossil fuel combustion by solar devices, either thermal collectors or PV panels [3]. The use of photovoltaic installations is continuing increasing worldwide since it represents a cleaner way of generating electricity with minimum impact to the environment. According to IRENA reports, the world power generation due to

PV systems in year 2019 has been of 578.6 MW [4]. Although this amount represents a low percentage of world energy production, is of great significance since it shows the growing trend of the technology and its increasing implementation in the energy market.

The best use of PV systems is either on place or in the nearby of the energy consumption centers, since the power losses are minimized. To this goal, the placement of PV panels on top of the industrial buildings may represent a good solution to supply electricity to the industry at minimum cost. Even if the power supply does not cover the full energy requirements, it represents a significant reduction of fossil fuel dependence and an important

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contribution to the reduction of carbon emissions and the environment preservation.

One of the advantages of using PV installations in rooftops of industrial buildings is the reduction of CO₂ emissions in places where the pollution is high because of the high activity, the large amount of fossil fuel consumption, and the concentration of industries in a relatively small area. Nevertheless, to optimize the use of the rooftops it is required to elaborate a method that allows the user to place the PV panels in a way to cover the full area with minimum or no interference between panels; this is only possible through a modelling since every rooftop shows specific characteristics like size, orientation and shape.

The use of PV panels on the industrial building rooftops as a power source requires a perfect knowledge of the spot, since it determines the available area, thus the amount of energy the PV installation can supply. The images from geostationary satellites provide information for large areas. In past years, the image resolution has been largely improved, in space and time, from a spatial resolution of 2.5 km and a time resolution of 30 minutes [5], to a spatial resolution of only 1 km and time resolution of 15 minutes [6]; however, for higher space resolution the GIS system is required. Using GIS tools, we can easily achieve a spatial resolution of 5m per pixel with the help of LIDAR technology [7], which is more suitable for small spot areas such as industrial building rooftops.

Some of the former research studies the optimization of the spatial layout for photovoltaic panel installation on top of a building rooftop with not all space available [8], while others use the LIDAR technique to characterize rooftop angular and dimension parameters [9] or the effects of shading [10].

A general review of the operation mode of the above programs has resulted in a series of drawbacks that may them not suitable for the calculation because of an arbitrary selection of the spot area. We propose the development of a new simulation process matching the type of application. This simulation takes into account all specific considerations, like the irregular shape of the spot, the individual size, its specific location, the tilt of the surface, which may be different for every case, and the precision required to supply a reliable estimation of the power and energy supplied by the PV installation.

The new simulation process combines with the LIDAR technology of high resolution, since the spot area of the proposed modelling is very small (5m x 5m). The use of the LIDAR technology provides a rapid solution of individual cases, thus reducing time consumption. It applies to a large number of cases with minimum effort and makes easier the comparison of results. LIDAR technology used for photovoltaic rooftop potential demonstrate the validity of the methodology [11].

The development of a reliable and accurate method to design the PV installation layout for every rooftop results in a better knowledge of the useful area, thus of the collected solar radiation and power and energy generation; this solution is not only technically convenient, but also economically suitable for the industrial building owner. The optimization of the PV layout also redounds in benefits for the electric network, since the increase of power and energy autonomy results in a reduction of energy distribution and infrastructure.

SPOT AREA MODELLING

To optimize the usable area 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 14N [12] with a latitude of 19°26' N and 99°39' W. The LIDAR images required for our study were taken applying the ArcMap tool shown in Figure 1.

The spot area was analyzed and classified according to its PV potential using LIDAR and GIS (Figure 2).



Figure 1. Geographical situation of the set up location (Toluca, México) [13]

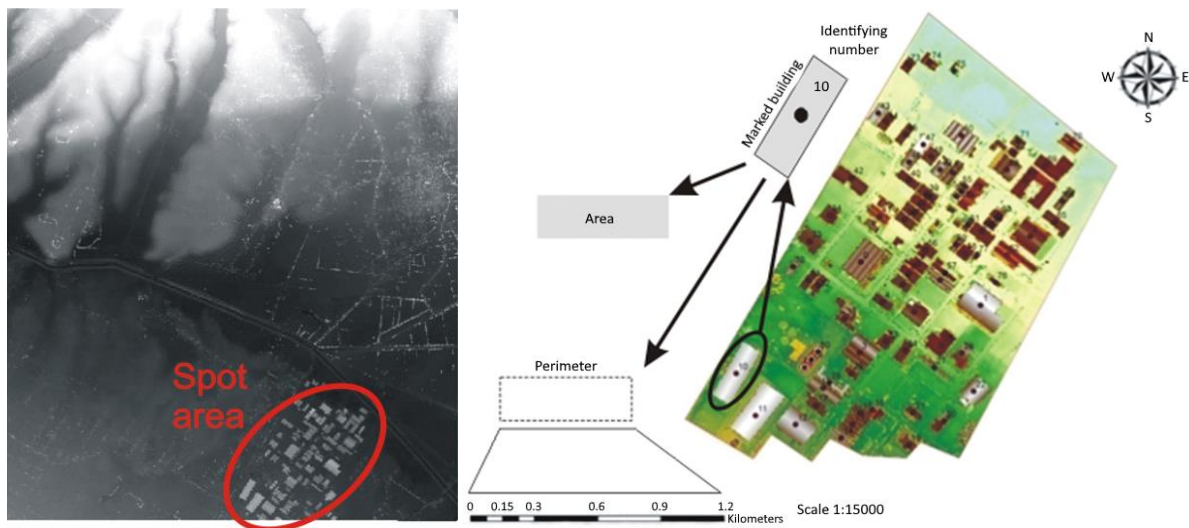


Figure 2. LIDAR image [14] (left) of the spot area (right) [15]

PV PANELS DISTRIBUTION

The distribution of the PV panels on a specific area like the industrial building rooftop requires the knowledge of the dimensions of the panel as well as the dimensions of the rooftop's area. Since the PV panel dimensions depend on manufacturer and model, it is necessary to normalize the panel shape to a standard relation between length and width; in our case, this relation is 2:1. On the other hand, the slope of the rooftop where the PV panels are placed also influences the PV layout; this parameter has been taken between 0° and 3° , which is a current value for the latitudes of the selected location. The dimensions and shape of the rooftop also depend on the type of industry; therefore, we have averaged the dimensions and shape of the industry buildings in several industrial conglomerates, obtaining that the shape keeps the proposed relation for the PV panel between length and width, 2:1, and the current length of an industrial building is 40 m. However, the industrial buildings are not placed next to each other, but keeping a distance between them. Once again, we have averaged the minimum distance between two adjacent industrial buildings in the industrial conglomerates, resulting in the layout shown in Figure 3. Figure 3 also shows a schematic layout of the PV panels on the rooftop.

Applying mathematical relations, we have:

$$L = \sqrt{2S} \quad ; \quad w = \sqrt{S}/2 \quad (1)$$

Where L , w and S are the length, width and area of the rooftop, respectively.

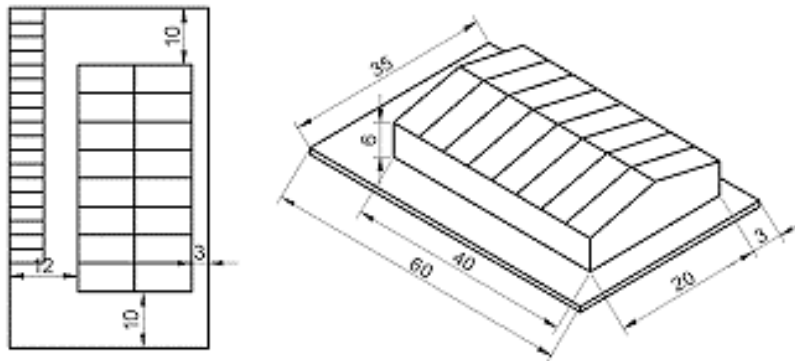


Figure 3. Modelling of the PV layout on top of the rooftop

Taking into account the shading effect caused by the tilted panels, we establish the minimum distance between rows, which can be determined from the expression [16]:

$$D = \frac{z}{\tan \theta} + \frac{z}{\tan \beta} = L_{PV} \left(\frac{\sin \beta}{\tan \theta} + \cos \beta \right) \quad (2)$$

Where L_{PV} is the length of the PV panel, β is the tilt angle, and θ the angle of incidence of the solar radiation onto the panel.

Since the angle of incidence depends on the declination according to the expression:

$$\theta = 90 - \phi - \delta \quad (3)$$

The minimum distance for the maximum shading effect is:

$$D = L_{PV} \left[\frac{\sin \beta}{\tan (90 - \phi - 23.5)} + \cos \beta \right] \quad (4)$$

To optimize the number of PV panels in the rooftop's area we have established the following premises for the model development:

- All the rooftop's area is suitable to place PV panels
- The panels are distributed in rows and columns covering all the area
- Rows are separated each other by the distance established in equation (4)
- Columns are separated by a minimum distance to allow maintenance service; this distance has been taken as 0.5 m
- Frame of the panel is included in the global dimensions

MODELLING

Surface and PV panel oriented to the Equator

The model makes use of the GIS tools to determine the dimensions of every industrial building rooftop in the reference industrial conglomerate made up of 34 buildings, as well as their orientation and tilt. Applying GIS to the industrial conglomerate we have noticed that most of the industrial building rooftops are oriented SW. Table 1 indicates the corresponding area of every industrial building rooftop, while Table 2 shows the orientation.

Table 1. Area of the industrial buildings for the reference conglomerate

Id	1	2	3	4	5	6	7	8	12
Rooftop area [m2]	15575	6775	7475	3475	2550	1650	1725	1600	9275
Id	13	14	15	17	18	19	25	26	29
Rooftop area [m2]	3225	1375	17252	1625	2625	1050	4075	2400	650
Id	33	35	37	40	41	42	52	56	62
Rooftop area [m2]	6200	2650	1850	1425	16003	3850	2800	1550	6150
Id	64	68	69	70	71	72	75		
Rooftop area [m2]	850	13754	4950	2450	875	625	175		

Table 2. Orientation of the surface of the industrial buildings for the reference conglomerate

Id	1	2	3	4	5	6	7	8	12
Azimuth (°)	221	213	213	223	234	216	220	205	221
Id	13	14	15	17	18	19	25	26	29
Azimuth (°)	219	221	222	227	218	214	221	208	208
Id	33	35	37	40	41	42	52	56	62
Azimuth (°)	226	219	225	220	214	217	219	218	216
Id	64	68	69	70	71	72	75		
Azimuth (°)	221	219	218	219	220	240	227		

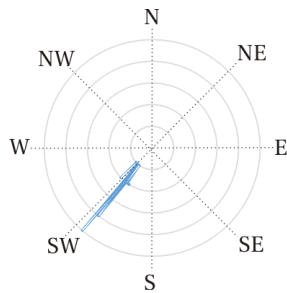


Figure 4. Compass rose of the orientation of the industrial conglomerate

The values in Table 2 show that most of the industrial buildings have an orientation close to SW (225°), with a mean value for the cluster of 220°. Figure 4 shows the representation of the compass rose corresponding to the orientation of the conglomerate of industrial buildings.

To determine the number of panel we have used the Python program [17, 18] following the next flow chart (Figure 5):

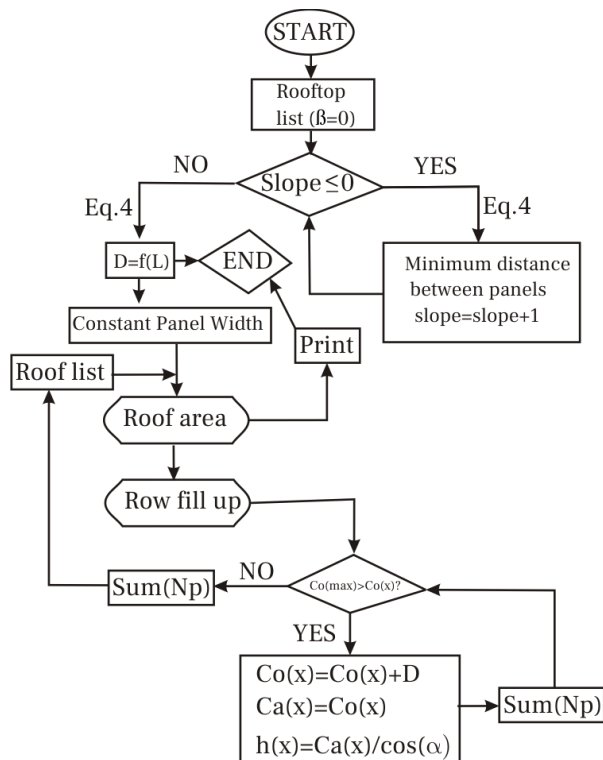


Figure 5. Flow chart of the Python program

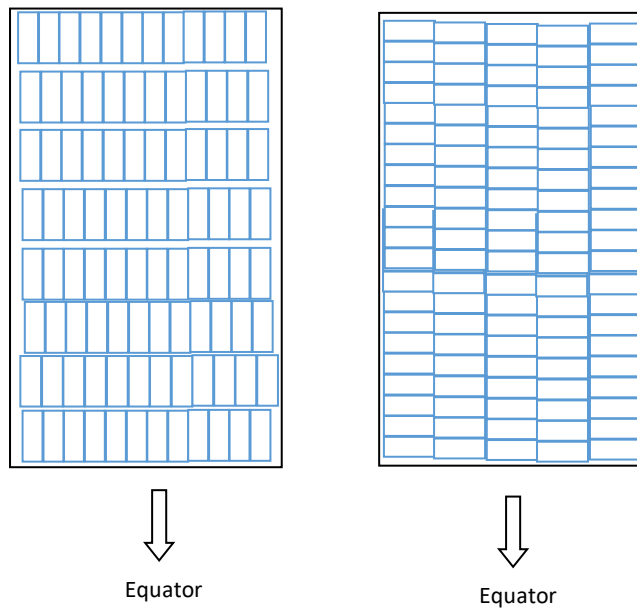


Figure 6. Ideal PV layout

First simulation of the modelling has applied to ideal conditions where rooftop's surface and PV panel are both oriented to the Equator. In such conditions, we have a PV layout as represented in Figure 6. This figure shows the ideal conditions where the PV panels are lying on the surface for a tilt angle of 0° . In these conditions, the PV layout covers the entire rooftop's area, and the number of panels is maximum. From the rooftop's area and the area of the PV panel, including frame, we obtain the maximum value of the number of panels. Since the area of the industrial buildings rooftop is not the same, we have averaged all areas to obtain a representative value of the industrial conglomerate.

Left: vertical configuration; Right: horizontal configuration

$$\langle N_p \rangle = N_p^o = \frac{1}{n} \frac{\sum_{i=1}^n S_i}{A_p} \quad (5a)$$

Where n represents the number of industrial buildings, S_i the area of every rooftop, and A_p the area of the PV panel.

Using data from Table 1 we have obtained:

$$N_p^o = \frac{1}{34} \frac{108225}{1.7085} = 1863 \quad (5b)$$

Due to the shading effect, the panels separate each other the distance indicated by equation (4), thus the number of panels changes with the tilt angle.

Tilt angle can be in the range 0° to 90° ; however, in practice, it adopts the value of the latitude of the location, which in our case, is 20° , the top tilt angle.

As a common practice, all PV installations in the North hemisphere are positioned facing to the Equator because this is the orientation that collects the maximum daily solar energy; therefore, we have developed a model in which all PV panels have been considered facing to the Equator. On the other hand, because of the rectangular shape of the PV panel, its positioning may adopt two configurations, vertical or horizontal; therefore, we apply the modelling to any of these configurations.

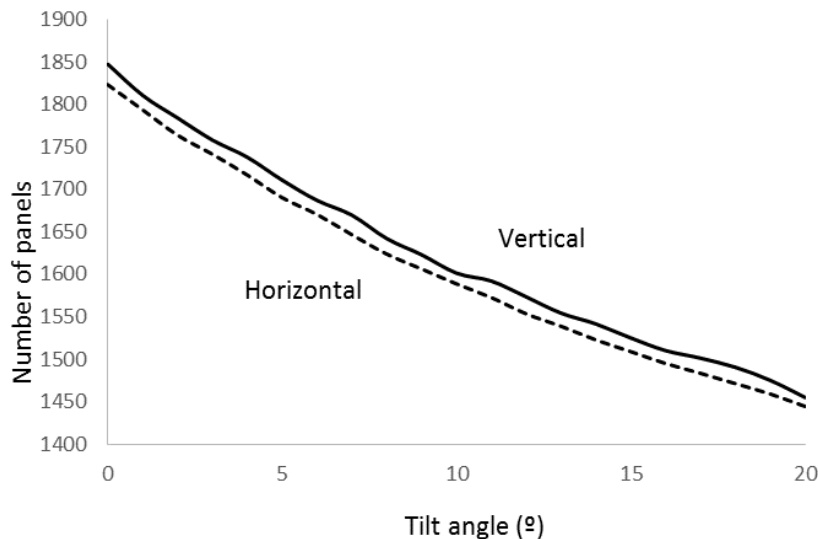


Figure 7. Number of panels for ideal conditions; rooftop and PV panel oriented to the Equator

Applying these conditions to the simulation and using the Python program described before, we are able to determine the number of panels for tilt angles between 0° and 20°. We show the results of the modelling process in Figure 7.

We notice from the results presented in Figure 7 that number of panels reduces as the tilt angle increases. This is due to the increased shading effect that forces the distance between panels to be increased, thus reducing the number of them.

We can also observe that vertical configuration works better than horizontal, because the number of PV panels is higher. However, the difference is not very significant, since the average value of the difference is about 1.1% with a maximum deviation of 1.4%. Therefore, we can conclude that vertical configuration is better, but not critical.

Adjusting the values of Figure 7 to a linear regression:

$$N_p = \begin{cases} -18.552\beta + 1791.4 & (R^2 = 0.982) \text{ (horizontal)} \\ -18.815\beta + 1811.5 & (R^2 = 0.982) \text{ (vertical)} \end{cases} \quad (6)$$

Equation (6) allows determining the number of PV panels for ideal conditions, rooftop and panels oriented to the Equator. The high values of the regression coefficient validates the linear regression and the methodology to calculate the number of PV panels.

Comparing the value from equation (5b) with the one obtained from the modelling we observe the good agreement, especially for the vertical configuration; this agreement proves the validity of the method. The deviation between ideal PV layout and model results is 0.8% for the vertical configuration and 2.1% for the horizontal one.

Surface with azimuth and PV panel oriented to the Equator

For the real situation, where the industrial conglomerate are oriented SW, we have the following representation of the PV layout (Figure 8). This representation considers the PV panels have the same orientation than the industrial building rooftop to preserve the maximum of the number of the installed panels. However, this configuration penalizes the collection of daily solar radiation, since it is not symmetrical respect to the solar noontime. To avoid this situation, the panels should keep oriented to the Equator and the configuration evolves as shown in Figure 8.

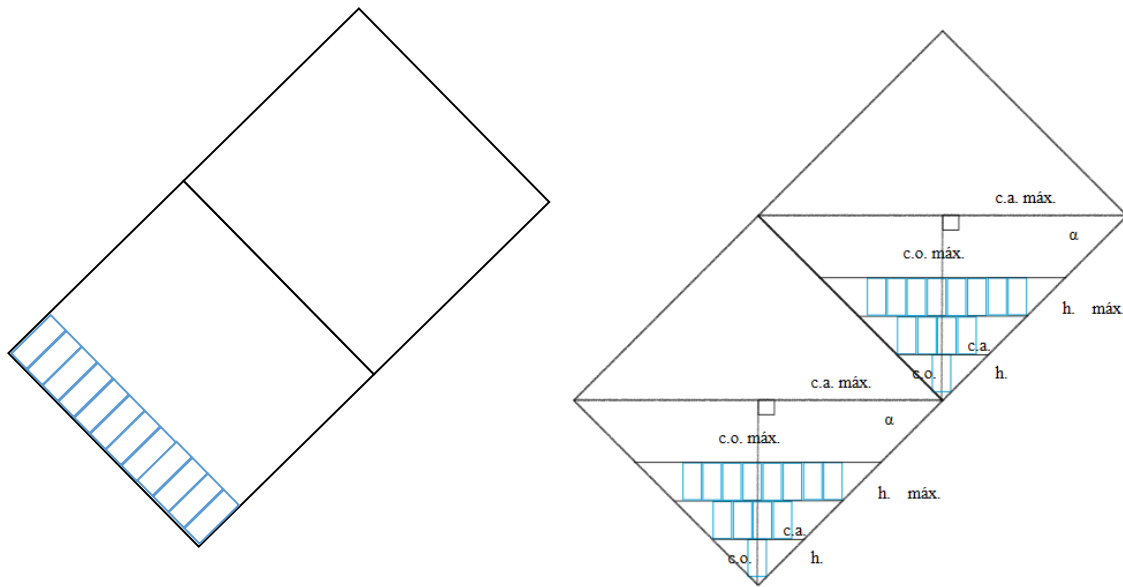


Figure 8. Graph representation of PV panels' distribution for rooftop surface oriented to SW. Left side: PV panels oriented to SW; Right side: PV panels oriented to the Equator.

In this case, the PV layout does not cover the full area of the rooftop, thus we have to determine the fraction of the area that is covered.

The proposed situation implies to rotate the representative plane of the PV panel respect to the rooftop's plane an angle equivalent to the azimuth of the industrial building. Applying GIS tools we can obtain the orientation of every industrial building, so the azimuth, and rotate the plane consequently.

The rotation of the PV panel generates an “oversizing” effect because the rotated plane leaves a “free space” between panels that is useless for energy collection. This free space is the consequence of the mismatching between the PV panel oriented to the Equator and the rooftop's surface oriented at an azimuth γ . The result of this “oversize” effect is the effective reduction of usable area on the rooftop for PV panel installation, thus a reduction in the global PV panel layout area and in the energy supply.

We use a mathematical treatment to obtain the reduction in the usable area of the problem. Let us consider the PV panel rotates an angle γ , equivalent to the azimuth of the rooftop (Figure 9); the area of the PV panel, using Cartesian coordinates in the reference plane, is:

$$S = LW = 4x_o y_o \quad (7)$$

Where L and W are the length and width of the PV panel, and x_o, y_o the Cartesian coordinates of the vertices, assuming the panel is rectangular.

For the rotated plane the coordinates of the vertices are named (x_1, y_1) , (x_2, y_2) , (x_3, y_3) and (x_4, y_4) . These coordinates relate to the original coordinates in the following way:

$$\begin{aligned} x_1 &= x_o \cos \gamma + y_o \sin \gamma ; y_1 = y_o \cos \gamma - x_o \sin \gamma \\ x_2 &= x_o / \cos \gamma ; y_2 = y_o \cos \gamma + x_o \sin \gamma \\ x_3 &= y_o \sin \gamma - x_o \cos \gamma ; y_3 = y_o \cos \gamma - x_o \cos \gamma \cot \gamma \\ x_4 &= x_o / \cos \gamma ; y_4 = x_o / \sin \gamma \end{aligned} \quad (8)$$

The area of the PV panel is be defined as:

$$S' = L'W' = (x_1 - x_2)(y_2 - y_4) \quad (9)$$

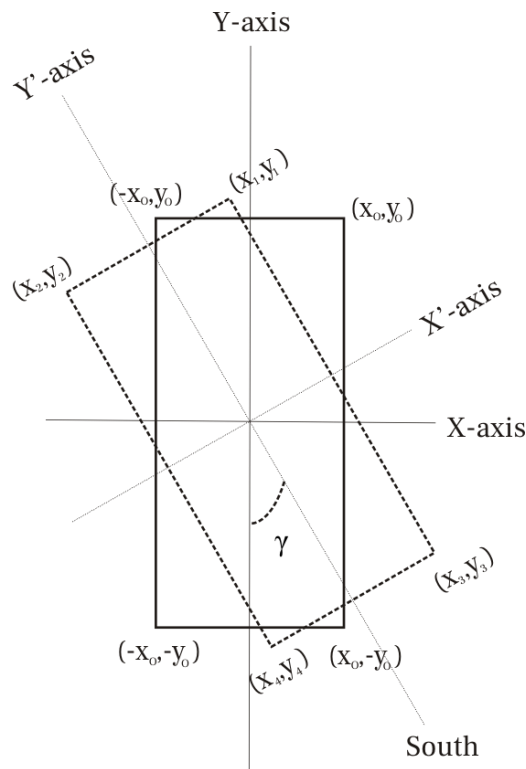


Figure 9. Graph representation of the rotation effect of the PV panel

Therefore, operating in coordinates of the original reference plane, we have:

$$S' = (x_0 \cos \gamma + y_0 \sin \gamma + x_0 / \cos \gamma)(x_0 / \sin \gamma + y_0 \cos \gamma + x_0 \cos \gamma) \quad (10)$$

Knowing that $L=2y_0$ and $W=2x_0$, equation 10 transforms in:

$$S' = (1/4) \left[3LW + L^2 \sin \gamma \cos \gamma + W^2 \left(\frac{2 + \sin^2 \gamma \cos^2 \gamma}{\sin \gamma \cos \gamma} \right) \right] \quad (0 < \gamma < 90) \quad (11)$$

Which gives the effective surface used by the PV panel including the free space around it.

Comparing equations 7 and 11, we can obtain the surface coverage factor, defined as the ratio between the original area given by the equation 7 and the “oversizing” one from equation 11. In such a way:

$$F_s = 1 - \frac{S}{S'} = 1 - \frac{LW}{(1/4) \left[3LW + L^2 \sin \gamma \cos \gamma + W^2 \left(\frac{2 + \sin^2 \gamma \cos^2 \gamma}{\sin \gamma \cos \gamma} \right) \right]} \quad (0 < \gamma < 90) \quad (12)$$

Operating in equation 12, we have:

$$F_s = 1 - \left[0.75 + \frac{L}{W} \sin \gamma \cos \gamma + \frac{W}{L} \left(\frac{2 + \sin^2 \gamma \cos^2 \gamma}{\sin \gamma \cos \gamma} \right) \right]^{-1} \quad (0 < \gamma < 90) \quad (13)$$

An expression that allows determining the effective surface fraction covered by the PV layout as a function of the PV panel dimensions and the azimuth of the industrial building rooftop.

Considering an azimuth variation from 5° to 75° in steps of 5° , and supposing the length to width ratio of the PV panel is 2:1, which is a current shape for commercial PV panels, we obtain the following graph representation (Figure 10).

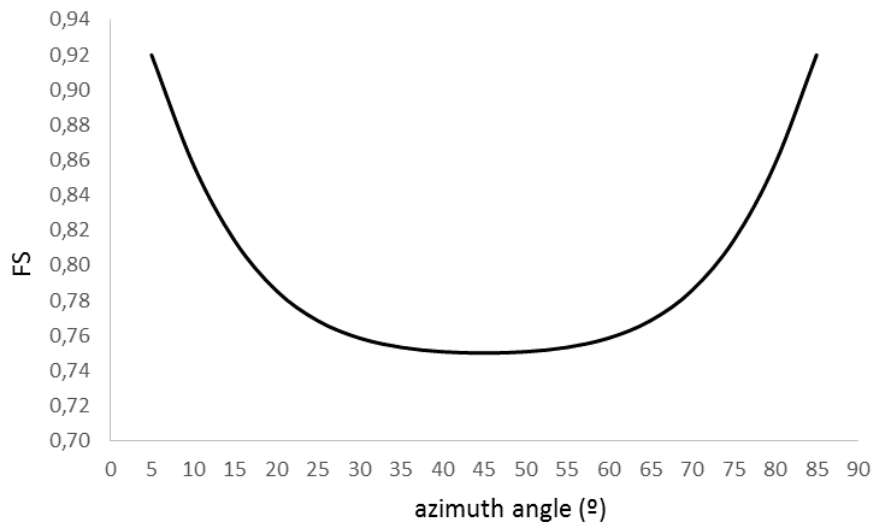


Figure 10. Surface coverage factor

The surface-covering factor decreases from the initial value of 5° down to the minimum for an azimuth of 45°, then increasing up to the final value of 85°. This is consistent with the fact that the half angle between zero and 90° represents the minimum surface coverage factor in a geometric representation for regular surfaces of rectangular shape.

Applying the modelling simulation to the new conditions, we have (Figure 11):

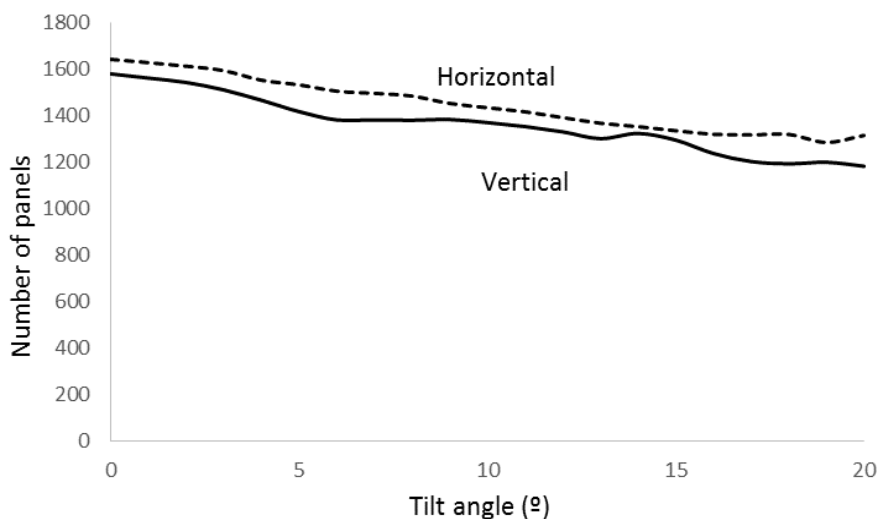


Figure 11. Number of panels for rooftop oriented to SW and PV panel oriented to the Equator

Figure 11 shows the horizontal configuration of the PV panel positioning works better for rooftop surfaces not facing to the Equator, in opposition to the case of orientation to the Equator where the vertical configuration provides better results.

Using a linear regression to adjust the behavior of the number of panels with tilt angle, we obtain:

$$N_p = \begin{cases} -18.632\beta + 1633.7 & (R^2 = 0.9745) \text{ (horizontal)} \\ -19.239\beta + 1555.3 & (R^2 = 0.9562) \text{ (vertical)} \end{cases} \quad (14)$$

The high regression coefficients for both configurations proves the validity of the adjusting linear regression.

Equation (14) allows the user determining the number of panels provided we know the tilt angle of the PV panels.

Calculation of the optimum number of PV panels

For an oriented rooftop surface with azimuth γ and PV panels tilted an angle β , we combine equations (5a), (13) and (14) to determine the optimum number of PV panels that we can install on the rooftop's surface, obtaining the following expression:

$$N_p = -18.632\beta + F_S N_p^o \quad (15a)$$

For PV panel vertical configuration, and

$$N_p = -19.239\beta + F_S N_p^o \quad (15b)$$

For the horizontal one.

Equation (15) gives an easy way to determine the optimum number of PV panels installed on top of an industrial building rooftop for any orientation of the rooftop and any tilt of the PV panel.

The error in determining the optimum number of PV panels derives from the accuracy of every of the involved equations, resulting in the following value:

$$\varepsilon(N_p) = \frac{a\Delta\beta + \beta\Delta a + F_S\Delta N_p^o + N_p^o\Delta F_S}{a\beta + F_S N_p^o} \quad (16)$$

Where $a = -19.239$ and:

$$\Delta N_p^o = N_p^o \left(\frac{\Delta \bar{S}_{roof}}{\bar{S}_{roof}} + \frac{\Delta A_{pV}}{A_{pV}} \right) \quad (17)$$

Where $\bar{S}_{roof}$ is the average value of the rooftop's surface of the industrial conglomerate, and A_{pV} is the area of the PV panel.

Since tilt angle and surface coverage factor are variable, we take the maximum value of these two magnitudes in their respective intervals to maximize the error.

Applying absolute error values to the magnitudes involved in equations (16) and (17):

$$\Delta N_p^o = 1863 \left(\frac{25}{108225} + \frac{0.01}{1.709} \right) = 11.3 \quad (18)$$

$$\varepsilon(N_p) = \frac{(19.329)(1) + (20)(0.001) + (0.920)(11.3) + (1863)(0.001)}{(19.329)(20) + (0.920)(1863)} = 0.015 = 1.5\% \quad (19)$$

Equation (19) indicates the error in calculating the number of PV panels is very low, what proves the validity of the proposed modelling.

The general procedure to determine the optimum number of PV panels is as follows:

- Geometrical calculation of the number of PV panels based on the rooftop's surface and PV panel area (N_p^o). In case this calculation is applied to an industrial conglomerate the rooftop's surface corresponds to the average value for the entire conglomerate (eq. 5)
- Application of the "surface coverage factor", F_S , to determine the number of Equator oriented PV panels, N_p , on an industrial building rooftop with azimuth γ (eq. 13)
- Reduction of the number of PV panels due to the tilt angle β . Vertical or horizontal PV panel configuration should be used accordingly (eq. 15)
- Correction of the final value by the corresponding error (eq. 19)

CONCLUSIONS

The proposed model allows determining the optimum number of PV panels on top of a rooftop based on the type of configuration of the PV panels, horizontal or vertical, the tilt angle of the PV panel and the azimuth of the rooftop. Modelling tests have been carried out for rectangular panels with a length to width ratio of 2.

Two types of PV panel configuration have been tested, vertical and horizontal. For PV panels and rooftops oriented to the Equator the vertical configuration works better; however, when the rooftop's surface has an azimuth and PV panel keeps oriented to the Equator, the horizontal configuration gives better results.

The dependence of number of PV panels on the tilt angle for rooftops and PV panels oriented to the Equator has been modelled and simulated. The evolution of the number has been adjusted to a linear regression within accuracy of 98.2%, both for vertical or horizontal PV panel configuration. Algorithms have been developed to determine the numbers of panels as a function of the tilt angle for vertical and horizontal PV panel configuration.

Model has been applied for tilt angles of the PV panel from zero to 20°, corresponding to latitudes up to 20°, if tilt angle equals the latitude, but is also valid for higher latitudes.

Modelling allows determining the useful fraction of the rooftop's surface through a parameter called "*surface coverage factor*". The model predicts the evolution of the factor with the azimuth of the rooftop for PV panels oriented to the Equator. The "*surface coverage factor*", F_s , has been developed for azimuth angles up to 85° and its accuracy is higher than 99.5%. Minimum surface coverage factor is 75%, which occurs for an azimuth of 45° and increases up to 92% for angles of 5° and 85°.

The optimum number of PV panels is obtained through a specific algorithm that depends on the tilt angle, the surface coverage factor and the ideal maximum number of PV panels, which corresponds to non-tilted PV panels onto a horizontal rooftop surface.

The maximum error in determining the optimum number of PV panels is 1.5%, which proves the high accuracy of the method and its validity.

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