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Analysis of Structures for Photovoltaic Panel Supports

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Abstract: This study designs and sizes several rooftop mounting systems for photovoltaic panels, taking into account the different wind and snow loads that impact these structures across a range of locations. In order to model these photovoltaic panel support structures, made of aluminium or steel, both geographical location and panel tilt angle were incorporated through the engineering software CYPE. The final step was to evaluate the advantages and disadvantages of the various structures designed with different materials and dimensions. Aluminium mounting systems were found to be more resistant and are also 80% lighter than steel ones; however, their price is 20% higher than those structures made of steel.

Key words: mounting systems, photovoltaic panel, analysis, design, calculation

1. Introduction

This study evaluates and models real cases that comply with the Spanish Technical Building Code's [1] requirements and consider the range of possible wind and snow loads found across all of Spain's provincial capitals. Therefore, the calculations, results, and conclusions of this study are valid for the entire country of Spain.

This project has come about during a boom in photovoltaic solar energy, and for renewable energy in general around the globe. This exponential growth can be attributed to factors such as: decreasing costs for acquiring and installing solar panels, increasing social awareness of global warming and climate change, development of self-consumption models, and the fact of that these types of investments now offer great economic and social returns. For example, recent studies have developed building integrated photovoltaic modules where photovoltaic panels are installed in the vertical façade of residential and office buildings to produce more electricity and reduce seasonal mismatch [2]. Meanwhile, other studies generate photovoltaic energy for self-consumption and distribution by designing a thin photovoltaic film that is integrated into the facade of industrial buildings [3]. On the other hand, if we turn to the mounting systems used for rooftop photovoltaic panels, the types of mounting structures can be divided into two categories: depending on whether the structure is installed on a sloped roof, which is common in single-family homes where smaller systems are the norm; or on flat roofs, which are more standard in industrial buildings with larger photovoltaic systems. These mounting systems consist of two components: the support structures, which are the focus of this study, that are mounted directly on the roof; and the solar panels which are fixed atop these supporting frames. There are also numerous studies of structures that hold solar panels in a variety of other environments: such as the finite element analysis of floating photovoltaic modules in inland Waters [4]. Other studies design and analyse support systems for solar panels used in agriculture that focus on structural efficiency under high wind loads [5]. Meanwhile, other research analyses wind load and a wind-load distribution model for solar panels, given that wind load is the main factor leading to structural failure in support systems [6]. Yet another study proposes a structure for a solar power

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system capable of operating stably in the areas of weak terrain. This study used numerical analysis to calculate various load distributions and structure deformations. The typical characteristics of the terrain of the areas under study were taken into consideration to determine which system minimized settlement to the greatest extent [7]. The integration of these systems in buildings must take into account several factors: the scale, and parameters of this integration in different climatic zones [8]. An example of this type of study is found in the evaluation of the performance of different solar modules and assembly structures in a photovoltaic system connected to the grid in south-central Chile **错误!未找到引用源。**.

The initiative presented herein encompasses the study, design, sizing and cost evaluation of different mounting structures for rooftop photovoltaic panels, in order to offer technically and economically viable solutions for industrial, commercial, environmental and sustainability, facilitating and enhancing the use of urban and industrial land built for the production of photovoltaic solar energy through the creation of solar farms on industrial and residential roofs. To this end, a great deal of research was conducted to deepen our knowledge of the stresses involved in modelling photovoltaic-panel support structures, those being primarily wind and snow. Then, once the different types of support structures were designed, they were modelled and calculated in accordance with the various possible environments. Once these calculations were completed and the designs tested, an analysis of both base materials' impacts on price and mechanical resistance was conducted. The foremost challenges encountered during this process were, on the one hand, the discretization of the different calculation assumptions, since the combination of wind and snow loads and the panel tilt angles presented a large number of possibilities. And on the other, the different types of support structures had to be adapted to the needs of industrial production. These designs make improvements in relation to the Sustainable Development Goals (SDGs):

- Affordable and clean energy
- Sustainable cities and communities.

The report describes the different options proposed for the structures, as well as their advantages and disadvantages in each specific case.

2. Material and Methods

After the introduction and abstracts, this section describes the methodology used in this study.

Prior to designing the support structures, the first step was to determine the technical aspects and dimensions of the photovoltaic panels that would be suitable for said support structures. To this end, various solar panels on the market were analysed, along with their foremost advantages and disadvantages.

This study initially intended to examine solar panel configurations of 36, 60, and 72 photovoltaic cells. However, the 36-cell panels were eventually discarded because the cells are small in terms of size and power for the purposes of this project; and furthermore, they are not commonly utilized in large-scale industrial plants. The design implemented herein for solar-panel mounting structures is valid for 60 and 72-cell solar panels. Though for analysis purposes, the second one was utilized because it´s greater surface area entails increased exposure to snow and wind loads and therefore, its loads are more restrictive. These solar panels have the following dimensions: 2×1 meters, 25 kg; and a generating power of 380 W.

Once the type of solar panels to be attached to the metallic support structures was determined, the loads that these structures would be subject to were calculated by referencing the Spanish Technical Building Code. For the purposes of this project, the loads were divided into two categories: loads derived from permanent actions, such as the self-weight of both the support structure and the solar panel; whereas the second type of load is due to variable actions, like snow and wind.

The most significant challenge in terms of modeling and calculation lies in the variable actions, as they generate loads greater than those of self-weight. The loads generated by wind, also known as static pressure, move perpendicularly against the exposed surface and are calculated by multiplying: the value of the wind dynamic pressure, which depends on geographical location; by the exposure coefficient, which varies in accordance with location elevation and the degree of environmental harshness; by the wind or pressure coefficient, which depends on the shape and orientation of the panel surface with regards to wind, and for which negative values indicate suction loads and positive values, pressure loads. All of the foregoing is multiplied by the vertical projection area of the volume created by the panels that are under examination, that is, the sine of the tilt angle of the solar panel, multiplied by the surface area of the panel. In this project, the structure height considered for the exposure coefficient was 12 meters, so that the calculations would be valid for the vast majority of roofs in industrial buildings and sports stadiums.

The equation applied is shown below:

$$\mathrm{q_e} = \mathrm{q_b} \cdot \mathrm{c_e} \cdot \mathrm{c_p} \cdot \mathrm{Sen}\ \alpha \cdot \text{Área} \qquad (1)$$

Being:

- qe the static pressure of the wind.
- qb the dynamic wind pressure.
- ce the exposure coefficient, variable with the height of the point considered
- cp the wind or pressure coefficient

Loads generated by snow move vertically in a downward direction and are calculated by multiplying the characteristic value of snow load on horizontal ground, by the shape coefficient, which depends on the tilt angle of the panel; and by the horizontal projection area of the volume created by structure under study, that is, the cosine of the tilt angle of the solar panel, multiplied by the surface area of the panel.

$$q_n = \mu \cdot S_k \cdot Cos\ \alpha \cdot \acute{A}rea \qquad (2)$$

Being:

- qn snow load
- μ shape coefficient of the cover
- sk the characteristic value of the snow load on horizontal terrain

Now that we have selected and described the solar panels suitable for these support structures, as well their loads derived from permanent and variable actions, which the panels, in turn, transmit onto their supporting structure; the next step is to describe the structures themselves. The structure comprises two parts: purlins and angled frames.

The purlins are two straight parallel bars on which the solar panels rest: one purlin is located under the lower part of the panel and the other one, under the upper part of the panel. Each panel is attached to the purlins at four points: two points on the upper purlin on the lateral ends of the panel; and the other points on the lower purlin, also on the lateral ends on the panel. Thus, the purlins connect the solar panels to the angled frame; but they also serve to connect all the angled frames, thereby creating the supporting framework.

The angled frames, which consist of two bars set at an angle, are the part of the support systems that attaches the purlins to the roof's base material. The longer bar is set parallel to the solar panels and is where the purlins are attached. One end of this bar is anchored to the roof or the ground by small metal fixings, while the other end rests on the upper supporting bar. This second bar is positioned so that one end is anchored to the roof or ground, also by similar metal fixings, while the other end is attached to the longer bar: this point of connection serves to regulate the angle of the solar panel. If the desired tilt angle for the solar panels is 25°, the two bars forming the angled frame must be set at an angle of 90°. In the case of solar panels set at 30° angle, the upper bar of the angled frame must be attached vertically about 23 cm from the end of the longer bar. In order to obtain an angle of 35° for solar panels, the shorter bar of the angled frame must be also be in a near-vertical position, but it is connected to the other bar about 45 cm from its end.

The above-described configuration of angled frames and purlins was followed for all cases, although two different types of materials were used for the support structures: aluminum or steel.

Aluminium structures boast many advantages, the foremost being: lightness — aluminum that weighs about a third than steel. As a stainless material, aluminum is extremely resistant to corrosion and oxidation. And from a manufacturing perspective, it is easy to cut, handle, and shape. Steel, however, is notable for its great strength and resistance as compared to aluminum. Nevertheless, aluminum is more expensive than steel, which is its most significant drawback for industrial and commercial processes (Fig. 1).

Due to these materials' distinct properties, the supporting structures made from aluminum or steel have different characteristics in terms of shape and thickness, and therefore, different moments of inertia as well, which means that the structures made of one material or another will have different structural resistance (Table 1).

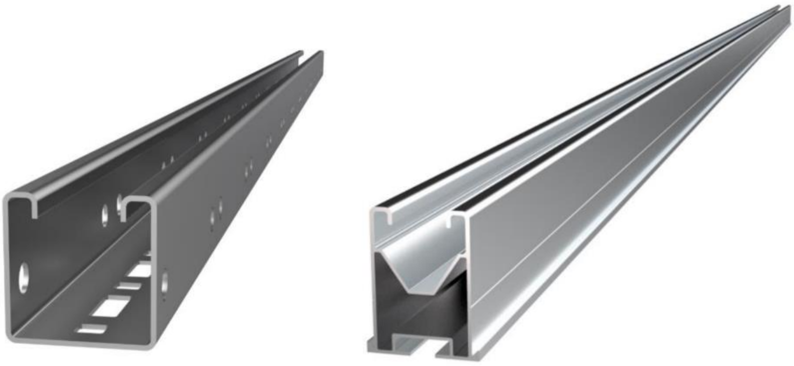

Fig. 1 Steel (left) and aluminium (right) support structure profiles.

Table 1 Technical characteristics of different designs.

Material	**Type of bar**	**Moment of inertia Y (cm^4)**	**Moment of inertia (cm^4)**	**Section Area (cm^2)**
Steel	Purlin	6.02	5.05	2.1
	Vertical			
	Tilted			
Aluminum	Purlin	16.93	11.29	4.15
	Vertical	4.81	4.81	2.64
	Tilted	5.2	7.55	3.08

The steel structures are simpler in terms of design due to their manufacturing and shaping process. They have a U-shape with two inward curved wings at the top that improve resistance without increasing height. The design of the different sized steel frames is the same in terms of purlins and angled frames; only the length of the bars varies.

Regarding the aluminum support structures, three different designs were selected for each type of bar in accordance with its requirements, that is: the purlin and the two bars forming the angled frame are different in terms of design, dimension and thickness. Such variety was possible because the aluminum designs were manufactured by extrusion; thus, specific designs could be made for each case and modifications could be made to adapt them to different needs.

Now that the design requirements have been detailed, as well as the solar panel selection process, and the loads applied to the support structures and the entire structure itself, along with the different materials and designs, we can now proceed to modelling and calculation in order to obtain conclusive results as to the stresses placed on the bars due to its structural configuration (Fig. 2), in each type of support structure located across all of Spain's provincial capitals. These stresses are derived from each case's respective wind and snow loads.

Fig. 2 Support structure.

To conduct this study, the engineering calculation software CYPE [10], in particular its module for metal structures CYPE 3D, was utilized to calculate support structures for two, three, four, five and six solar panels, since the combination of these different types of support structures covers all existing commercial needs, including their respective loads according to the abovementioned specifications and the dimensions indicated in the designs. Five cases in five different locations were selected to be examined given that they could be considered the most representative of all the provincial capitals in terms of the variable loads the structures have to withstand. These locations have been selected as references to cover the entire range of loads and have references in all locations of the peninsula in terms of the stresses to which the structures will be subjected in terms of loads. These locations are the cities of Leon, Soria, Lugo, Barcelona and Seville. The primary deciding factor in selecting case studies was snow load for the following two reasons: Firstly, the maximum and minimum values of snow load vary significantly according to data collected by the Spanish Technical Building Code: the minimum value being 0.2 kN/m² and the maximum value of 1.2 kN/m², which means a variation of up to 600%. Secondly, snow load has a more restrictive impact than wind load in vast areas of Spain, as the characteristic dynamic pressure wind load due varies between 0.42 kN/m² and 0.52 kN/m² and the characteristic snow load, as said previously, varies between 0.2 kN/m^2 y 1.2 kN/m^2, being a common load in the Spanish geography 0.6 kN/m^2, which is already bigger than the possible wind load.

After all the available data were compiled, the structures were calculated to verify how the different designs, materials, and configurations would perform. When analyzing the results, one must bear in mind that, although S235 steel is more resistant than 6063 aluminium, the moments of inertia were much higher for aluminum structures.

3. Results and Discussion

Now that all the parameters of this project have been defined, including the loads to which the structures are subject, materials, design, and tilt angle; and the structures have been completely modeled, we move on to analyzing the results obtained from a technical and economic standpoint.

From a technical point of view, the aluminum structure is valid for all the Spanish regional capitals on flat land without significant obstacles or trees. The solar panel installation can measure up to twelve meters, except in cases of extreme snow, where the snow load on horizontal ground is equal to or greater than 90 kg/m², according to Table 3.8 of the Spanish Technical Building Code's structural safety guidelines for construction. For such cases, a detailed study from a technical point of view of the location and applicable loads must be completed. An optimal solution would be to incorporate an additional angled frame in each support structure, thereby reducing the distance between the bars supporting the purlins. Fig. 3 indicates where aluminum structures are viable according to the established conditions.

On the other hand, for the S235 steel structure, all Spanish provincial capitals are viable, including urban, forested, and industrial land. This solar panel installation can be up to twelve meters tall, except in cases of extreme snow, where the snow load on horizontal ground is equal to or greater than 90 kg/m², according to Table 3.8 of the Spanish Technical Building Code's structural safety guidelines for construction, as long as the distance between angled frames where purlins are fixed do not exceed 1.5 meters.

These findings do not fulfill this study's original objective, since all those support structures in which the distance between fixing points on the purlins was greater than 1.5 meters had to be discarded (Fig. 4). Due to these results, it was decided to utilize a better performing type of steel in the study, given that this solution it's the simplest and more versatile, and its improved elastic limit is capable of fulfilling the objectives of the project. Because of this modification, the elastic limit of the steel used grew from 235 MPa to 355 MPa, which represents a 51% increase. And while this increase in the material's mechanical performance does not fully translate to an improvement in the structure's mechanical performance (which increased by 36%), it does clearly achieve an improvement in results, as can be seen in Fig. 5. These results are valid

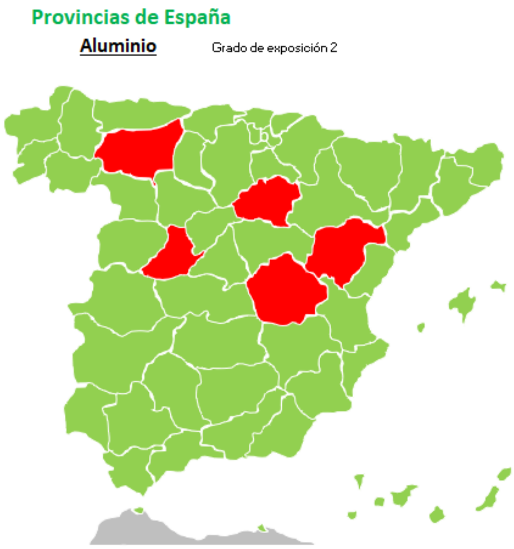

Fig. 3 Map of viable locations for aluminium structures.

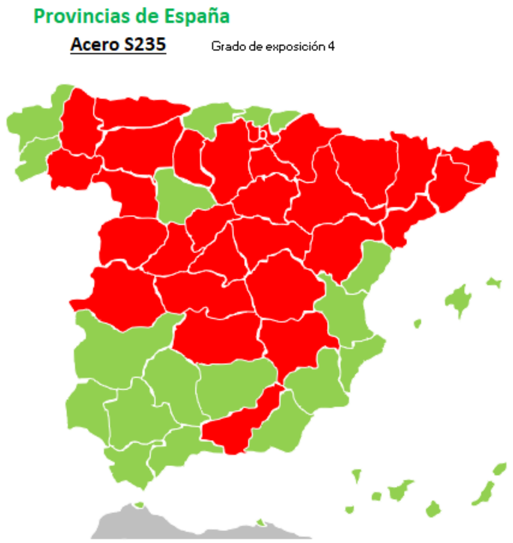

Fig. 4 Map of viable locations for Steel S235.

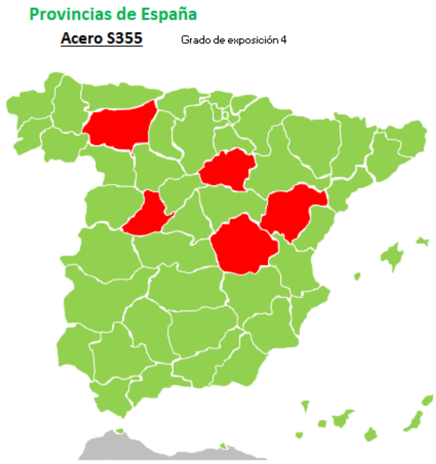

Fig. 5 Map of viable locations for steel S355.

for all the Spanish provincial capitals located in urban, forest and industrial lands, with solar installations of up to twelve meters above ground, except in cases of extreme snow, that is, the snow load on horizontal ground is equal to or greater than 90 kg/m² according to Table 3.8 of the Spanish Technical Building Code's structural safety guidelines for construction.

Replacing the initially planned S235 steel with S355 steel entailed an increase in price, but it turned out to be very small compared to the increase in resistance that was achieved.

Regarding the economic analysis of the results, once the solutions provided were proven valid from a technical point of view, the costs per solar panel were compared for the support structures of two, three, four, five and six solar panels depending on the base material used for the bars: steel or aluminum.

The difference in linear meters of material used is quite small. However, the designs have different weights per linear meter, which affects the total weight of the material used for each of the structures, as shown in Table 2.

The total weight of the aluminum structures is much lower than those made of steel, by around 85% on average. Nevertheless, the price of aluminum as a base material is much higher than that of steel, and this fact is reflected in the total price, which is approximately 20% higher for aluminum structures.

The results obtained herein indicate the viability of using these standardized models across the vast majority of Spain. These structures can be installed up to 12 meters above ground in industrial, urban and forest environments. This fact translates into great versatility for the construction of solar parks, and above all, for solar panels installed on the roofs of industrial buildings and sports centers. In those cases, involving extreme snow loads, a detailed study of each situation must be conducted.

A comparison of the results obtained for the different base materials reveals that aluminum, despite having less mechanical resistance than steel, performs better. This is because the aluminum designs were created to have higher moments of inertia which enhance its performance, along with its ease of installation and assembly. What's more, aluminum structures are lighter than those made of steel, which facilitates and reduces transport and installation costs. Nevertheless, the price of the base material is a decisive factor in terms of final cost for both types of structures, so it must be noted that steel is significantly cheaper than aluminum.

Table 2 Total weight of material used to depend on structure type.

Material	**2**	**3**	**4**	**5**	**6**
Steel (Kg)	15.35	23.23	26.692	34.57	42.03
Aluminum (Kg)	8.3	12.37	14.83	18.89	21.359
Variation (%)	84.92	87.91	79.95	82.98	99.79

4. Conclusion

Once a complete analysis of the project was conducted, the decision was made to carry out all the study cases, that is: support structures made from both base materials, using the three possible tilt angles (25°, 30° and 35°), for configurations of 2, 3, 4, 5 and 6 solar panels.

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This study helps to enhance the Sustainable Development Goals discussed in the proposed objectives, since they can be implemented as solar energy generation solutions taking advantage of the roofs of buildings in urban and industrial environments in order to achieve sustainable cities and communities. In addition, the implementation of renewable energy production projects in already urbanized environments stimulates the creation of affordable and non-polluting energy, especially reducing the landscape impact created by large solar farms installed in rural regions by taking advantage of the roofs of existing buildings that were currently not used for this purpose.

Therefore, it can be concluded that the support structures designed and modelled in this study fulfil market demands in terms of quality, ease of installation, weight, and mechanical properties. In addition, various alternatives have been proposed from an economic point of view. In terms of future research, these support structures could be designed with new, stronger, lighter, and more economical materials.

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