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Economic Feasibility of PV Mounting Structures on Industrial Roofs

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Abstract: This study determines the viability and profitability of photovoltaic (PV) mounting structures on industrial roofs. For this purpose, more than 656,000 different cases have been analyzed, combining different consumption patterns, energy prices, locations, inclinations, azimuths, capacity installed, and excess income. The results show that the industry's consumption pattern is a key factor, leading to significant reductions in the available assembly budget for inclined structures compared to the coplanar option when the pattern is seasonal and/or irregular. The increase in energy prices experienced in the last 2 years represents a substantial change in the viability of the structures. The budget for inclined structures increases by hundreds of euros compared to the coplanar option. Depending on the azimuth and inclination of the roof, the maximum available budget can vary by more than a thousand euros per kWp, being highly profitable in orientations close to the east and west and on roofs partially inclined to the north. Differences between low-irradiation and high-irradiation locations can mean variations in the average budget of more than 1 k€/kWp, especially with high electricity prices.

Keywords: photovoltaic; mounting structures; azimuth; inclination; industrial roofs; seasonality

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1. Introduction

The increase in energy prices experienced since mid-2021 has led to a significant rise in the energy bill, compromising the viability and competitiveness of many industries [1]. In this context, photovoltaic energy has been the main measure to mitigate the increase in costs in many sectors. The new context has significant effects on the viability and profitability of photovoltaic (PV) systems and their mounting structures, which, in many cases, are not taken into consideration. The adaptation to the new context requires adjustments in the sizing of PVs, which is also associated with changes in the return on investment [2]. In many cases, the design is carried out following established paradigms, with approximate calculations, without analyzing in detail the consumption pattern of the industry.

Load matching is an inevitable problem that restricts the development of PV systems used in buildings [3]. Optimal PV orientation should not only be based on maximizing energy production but also on expected demand patterns and market prices. In residential buildings, providing electricity not only around solar noon but also in the morning and late afternoon, when demand increases, helps to maximize self-consumption/-sufficiency and reduces costs for end-users and utilities [4]. Seasonality strongly conditions the optimal size of PV installations, the return on the investment, and the potential savings [2]. Differences between demand patterns caused large variations in optimal PV orientations [5].

Therefore, the optimization of PVs based on the consumption pattern has been analyzed in numerous specific cases, such as in residential buildings [5–7], commercial buildings [5,8], and military facilities [9]. Within the industrial sector, the causality is immense, with subsectors with many seasonal production industries, such as the agro-industrial [1]. For example, Jimenez-Castillo et al. [10] demonstrated the importance of optimizing the orientation and inclination in olive mills, based on the uniqueness of its consumption pattern, adapting it to seasonality. In wineries, seasonality was key in the profitability of the system for self-consumption, related to the optimum power to be installed in PVs [11].

The electricity tariff, which varies with the time of day and time of year, also impacts the optimal orientation of non-tracking PV modules [12]. Fitting the solar PV power generation curve according to the consumption curve is not always the most profitable way to optimize the orientation but also taking the electricity price curve into account is very significant when assessing profitability [13]. Therefore, a correct design of the PV must take into account the variations in the price of energy, carrying out a precise calculation of the resulting bill.

The optimization of azimuth and inclination on rooftops arouses great interest in the scientific community, with different approaches and criteria for decision-making depending on the application case. Maximizing the energy generated throughout the year is a common design criterion [14–21]. For a given location, the best-fixed orientation of a PV panel can be determined by achieving the maximum incident solar irradiance throughout the year [22]. A precise estimation of solar irradiation on a solar panel is critical for an optimal PV design [23].

Non-ideal inclination and azimuth angles can also lead to acceptable levels of electric energy generation [24]. A range for the optimal panel orientation according to the target loss can be used in decision-making for practical optimization of the PV panel [25].

Beyond the fixed PV mounting, several studies have analyzed the periodic change in tilt: daily, monthly, and/or seasonally optimum [26–31]. The monthly optimum tilt angle for a PV panel changes throughout the year [32]. Solar radiation energy is lost when using the yearly average fixed optimal tilt angle as compared with the monthly optimal tilt angle [33]. Although the daily optimal tilt angle produces the maximum energy generated, it is costly and impractical [34].

Optimization is also common taking into account economic and environmental criteria (through life cycle cost analysis) [9,35–39]. Cases with an inclination other than the one that maximizes energy can have economic and environmental advantages [35].

Optimization to minimize self-shading while accounting for practical considerations (ensuring rooftop walkability, distances required for maintenance, curtail the cooling load, etc.) has been analyzed in some papers [24,40–42]. There are also studies that have analyzed the optimal deployment of photovoltaic module rows installed on irregular flat roof shapes [43] and vertical installation of PV modules [44]. In modern structures, photovoltaic panels are being installed on different parts of buildings, resulting in panels mounted at various angles [45].

Although most studies focus on a specific city, several analyzed different locations, obtaining variations in the optimal inclinations [18,24,27,33,46–49]. On the contrary, Beringer et al. pointed to a reduced importance of panel tilt in mid-latitudes [50]. Therefore, locations with very different irradiance must be analyzed if a global view of PV optimization is to be obtained.

Despite the advantages that azimuth and inclination optimization may present, coplanar mounting is still frequently used on industrial roofs. This is due to its obvious advantages, including lower investment, greater simplicity, less weight, little visual impact, and less wind load. It is also attributed to the paradigms established in years of lower energy prices. However, structures that modify the orientation and/or inclination of the solar panels could be a much more profitable solution in the new energy context. The wide range of industrial roofs, from flat roofs to sawtooth roofs, with all possible azimuths, complicates the optimization of the PV. The optimization valid for one industry may not be suitable for another. In addition, in many cases, the limited space available raises the need to also take advantage of the most unfavorable roofs. A correct design of azimuth and inclination is key to the maximum profitability of the PVs.

Despite the numerous investigations on the subject, the extra cost and profitability of inclined structures versus coplanar structures have not been exhaustively analyzed. Most studies analyze the PV as a whole, without focusing on the best mounting option and the budget available for it based on the azimuth, inclination, and industrial demand pattern. This knowledge gap, coupled with the changes brought about by the new energy context, raises the need to carry out a study that provides a global vision of the economic viability of using PV mounting structures to change the inclination and azimuth of the panels on industrial roofs.

2. Materials and Methods

The study has quantified the available budget and the profitability of using mounting structures that improve the inclination and/or azimuth of the PVs, compared to a coplanar scheme. Specifically, two alternatives have been analyzed (Figure 1):

- Inclined structures on the roof to install solar modules in the optimal plane to maximize production, changing azimuth and inclination.
- Inclined structures on the roof, with the base of the panels parallel to the ridge. Only the tilt to reach the optimum inclination is modified, maintaining the roof azimuth.

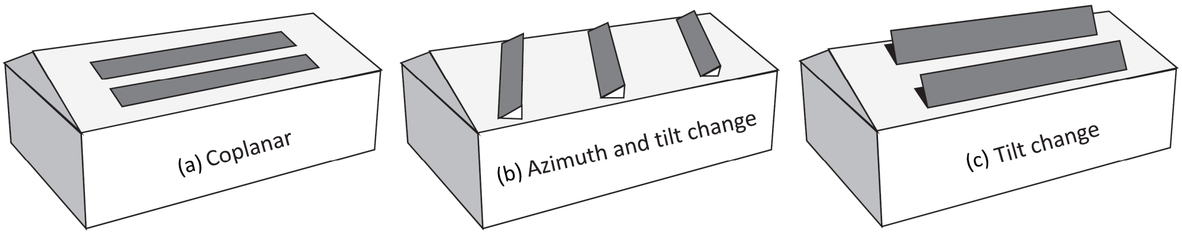

Figure 1. Alternatives analyzed for mounting the photovoltaic panels: (**a**) coplanar, (**b**) change in azimuth and inclination, and (**c**) change in inclination while maintaining the azimuth of the roof.

The suitability of optimizing the collection plane of the modules instead of using a coplanar structure is conditioned by numerous factors, such as the consumption pattern, the size of the PV (capacity installed), the azimuth and inclination of the industry's roofs, the solar radiation, electricity prices, or the income received from the production of electricity injected into the grid. All these factors have been analyzed through a precise calculation, reproducing a typical billing system of industries, carrying out a quarter-hourly energy calculation (Figure 2).

2.1. Quarter-Hourly Energy Analysis

The actual electricity billing system is usually based on data energy consumption collected every 15 min in almost every industry. Therefore, the energy analysis was carried out on a quarter-hourly basis. Industrial electricity consumption was compared with the electricity supplied by a PV system according to a certain installed capacity, with the objective of quantifying the reduction in grid energy consumption and the possibility of injecting electricity into the grid (as an upside). Variations in the Flash test report (test measuring the module's current–voltage (I–V) curve) are not taken into account, considering that the marked power corresponds to that of the photovoltaic module.

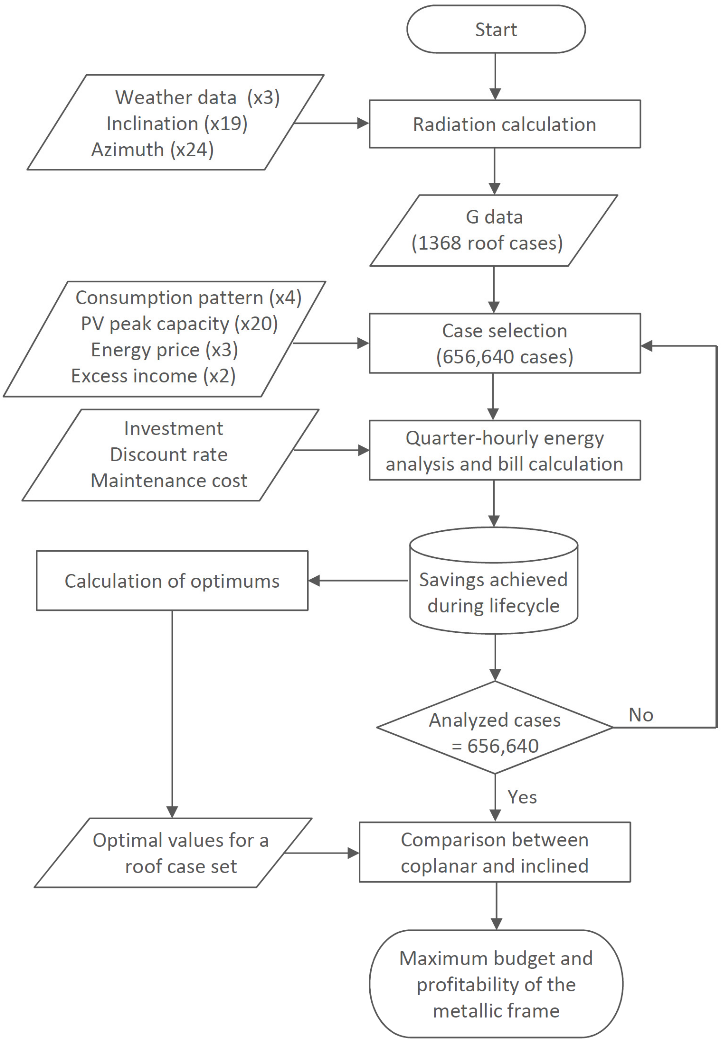

Figure 2. Methodology flowchart.

The equations used in the energy calculation have been previously evaluated and validated [2]. For each scenario, the energy supplied by the PV (E_{PV}, kWh) during each 15 min interval was calculated by multiplying the peak power of the system (P_{PV}, kWp) by the radiation on the inclined plane ($G, kW\ m^{-2}$), the duration of the interval (t, h), and by an overall efficiency of the system (μ_T , $-$) of 0.8 (Equation (1)). A similar level of efficiency (similar to the performance ratio) has been assumed in all cases with the objective of working under the same conditions. In a later section, the calculation of radiation on the inclined plane using the EnergyPlus software (https://energyplus.net/) is detailed.

$$E_{PV} = P_{PV} \cdot t \cdot G \cdot \mu_T \tag{1}$$

At any interval, the electricity produced by the PV system is compared with electricity demanded by the industry (E_D, kWh), calculating the electricity savings achieved by the PV on the bill to be paid (E_s, kWh), electricity acquired from the grid due to capacity limitations (E_G, kWh), and the excess energy produced by the PV (E_X, kWh) that could generate a certain level of income if country regulations allow for such an upside (Equations (2) and (3)).

$$If\ E_D \geq E_{PV}:\ E_s = E_{PV};\ E_G = E_D - E_{PV};\ E_X = 0 \tag{2}$$

$$If\ E_{PV} > E_D:\ E_s = E_D;\ E_G = 0;\ E_X = E_{PV} - E_D \tag{3}$$

In addition, in each quarter-hour interval, the new power demanded from the grid (P_G, kW) has been calculated by the difference between the power demanded by the industry (P_D, kW) and the effective power of the PV ($\frac{E_{PV}}{t}$, kW) (Equation (4)). According to this, any possible penalty applicable for excess power is calculated in a precise and realistic way.

$$P_G = P_D - \frac{E_{PV}}{t} \tag{4}$$

After calculating the electricity balances for each quarter of an hour of the year, the summation of energy supplied by the PV system (reduction in network consumption), energy demanded from the network that the PV could not supply, and energy injected into the grid (when exceeding demand) has been carried out in each of the tariff periods involved, reproducing the methodology used by the electricity providers.

2.2. Actual Impact on the Electricity Bill

In order to carry out a rigorous analysis of the savings generated by a photovoltaic system, it is necessary to reproduce an actual electricity billing system. The Spanish electricity pricing system has been used as a basis for calculation, with a fixed term for capacity and a variable term for energy, subject to a 21% value added tax (VAT) and excise tax of 5.11%. Electricity prices vary throughout each day according to 3 periods. Those periods are modified monthly basis, creating 6 periods with different price levels. Therefore, the impact on the PV system over the final bill depends on the time and month in which it occurs. Due to this fact, the methodology is based on an analysis with a quarter-hourly interval, calculating the annual amount of the expected bill based on 35,040 data.

A calculation tool based on "Visual Basic for Application" (VBA) was developed. This application is an evolution of a previously developed one to reproduce the billing of electricity companies, used as the basis for a recent publication [1]. The tool has been validated in scenarios without PV, using prices and consumption data from real invoices, verifying that the total amounts match.

An energy calculation module based on the previously described methodology has been added to the billing tool, which compares at each interval the real demand of the industry and the production of the photovoltaic system. From Equations (1)–(4), every 15 min, the electricity supplied by the PV, the electricity acquired from the grid, the energy savings achieved (compared to demand without PV), the excess energy produced by the PV injected to the grid (when the demand is less than the energy produced), and the new power registered are calculated. The tool has been validated with PVsyst in several cases on a random basis, selecting a PV system with an overall efficiency equivalent to that assumed and using the same radiation data.

After performing the energy calculations for each of the 35,040 intervals of the year, the new monthly bills and the resulting annual amount are calculated using the new values of energy and power demanded from the grid. The tool also provides monthly and annual summaries of the aforementioned energy variables. To do this, the billing tool reproduces the calculation of the electricity companies, taking into account price variations according to the period, the fixed term power, penalties for capacity excess, taxes, etc. In scenarios that include income from excess energy injected into the grid, the monthly and annual amounts are reduced by the profits generated.

2.3. Maximum Budget and Profitability of the Metallic Frame

A total lifecycle of the PV installation of 20 years has been assumed. This conservative hypothesis, with a shorter useful life than those considered by many investors, reduces the uncertainty of assuming an excessively long period in which substantial changes in the energy context are foreseeable.

The total updated savings achieved by the PV during the lifecycle have been calculated through the net present value (NPV) from the annual savings generated. For this, a discount rate of 2% has been applied, a value close to the interest rate on 20-year bonds in recent months in countries like Germany. A 1% of the investment was assumed as annual maintenance cost. Annual cash flows have been calculated by subtracting maintenance costs from the annual savings generated on the invoice.

In order to compare systems of different sizes, the total savings have been divided by the peak capacity installed in each case (k€/kWp). To compare the suitability of using inclined mounting structures versus the coplanar option, the maximum budget available for the inclined structure has been calculated based on the savings generated during the useful life of the PV system (calculated NPV) compared to that obtained without changing the azimuth and inclination of the industrial roof (coplanar).

In the case of structures that change the azimuth and inclination, the budget has been calculated as the difference between the savings achieved in the particular case of the roof (azimuth and inclination) and the optimal case that maximizes the energy, taking into account all possible azimuths and inclinations. In the case of structures that only change the inclination, the calculation has been equivalent, but taking as reference the maximum value of each azimuth instead of the total of the set of scenarios. The optimal values—-those with the highest energy production—have been identified through VBA programming among the set of cases defined in each analysis. The results have been stored in a database based on the characteristics of each specific scenario.

The available budget values thus calculated are the maximum possible, considering that panel installation does not create any shading. In some cases, especially those close to north orientation and with great inclination, the installation could involve shading if it is not carried out in the upper area and be limited to a single line of panels.

The casuistry of the mounting structures is very wide, from low-priced coplanars to complex and expensive structures that elevate the panels. The calculated budget quantifies the extra cost of the inclined structure compared to the coplanar, regardless of the type of material, its cost, etc., providing very useful information for the design of the PVs. However, to have a reference to compare profitabilities, the updated payback has also been calculated, assuming an extra cost of the inclined structure of 0.2 k€/kWp compared to the coplanar one, considering an inclined structure with a certain installation complexity.

2.4. Analyzed Scenarios

A total of 656,640 different cases have been analyzed, corresponding to the combination of 4 consumption patterns, 3 energy prices, 3 locations, 20 sizes of the PV, 19 inclinations, 24 azimuths, and 2 excess incomes.

2.4.1. Inclination and Azimuth

The aim is to quantify the impact of the inclination and azimuth of industrial roofs on the savings generated by the PV, determining the margin to incorporate structures that optimize the system. For this, 19 different inclinations were analyzed, from 0° (flat roof) to 90° (assuming structures attached to vertical enclosures on sawtooth roofs), with an interval of 5°. In turn, each of the previous inclinations was analyzed assuming different azimuths of the roof and/or the structure of the PV. Specifically, the 360° divided into intervals of 15°.

The incident radiation on each inclined plane has been calculated using the EnergyPlus program. For this, a nearly cylindrical construction was designed, similar to a mill, with the base being a polygon of 24 sides. The roof of the construction is also divided into 24 polygons, each oriented to a specific azimuth. When carrying out an annual energy simulation from this basic model and the climatological file of a given location, the program calculated the incident irradiation for each of the 24 surfaces that make up the roof, with a quarter-hourly interval. The rest of the variables that can be calculated with the energy simulation were discarded. To calculate radiation as a function of inclination, 19 different input data files were generated. In each one, the inclination of the polygons that make up the roof was modified, adapting them to the specific case. By carrying out the 19 simulations, which include 24 roof orientations each, a total of 456 different radiation scenarios are obtained for the same location. Furthermore, the simulations were calculated using 3 different climatological files, obtaining a total of 1368 cases.

2.4.2. Radiation

The calculations have been carried out in three locations with very different radiation. For the selection, the horizontal plane radiation data available in the EnergyPlus climatological files [51] have been used. After calculating the peak solar hours (PSH) of more than 200 locations, 3 cities were selected with values of 3.0 (Stuttgart), 4.0 (Rome), and 5.0 (Los Angeles). Specifically, the following climatological files (*epw) were used to carry out the simulations:

- DEU_Stuttgart.107380_IWEC.epw
- ITA_Rome.162420_IWEC.epw
- USA_CA_Los.Angeles.Intl.AP.722950_TMY.epw

2.4.3. Consumption Pattern

The seasonality and homogeneity of the demand pattern of industries could strongly influence the profitability of mounting structures. Therefore, the study has been based on four industries with very different consumption patterns:

- Autu_7d_Peak (Winery): It has a strongly seasonal demand, with large peaks of energy consumption and high power in August, September, and October. During these months, the processing of grapes for wine production takes place from Monday to Sunday. The rest of the year the energy demand is very small, mainly from Monday to Friday.
- Wint_7d_Peak (Olive mill): The demand pattern is very similar to that of the first industry, but concentrated in December, January, and February. In addition, the power required by the machinery used in olive milling and processing is somewhat lower than in the previous case.
- Year_7d_Unif (Fruits and vegetables): The industry presents a very stable and uniform pattern throughout all months of the year. The cooling equipment demands energy every day of the week, with a stable maximum power, much lower than in the previous cases.
- Year_5d_Peak (Feed factory): As in the previous case, it has very stable energy consumption throughout the months. However, its energy demand is concentrated during a few hours a day, from Monday to Friday, registering large peaks of power.

The selected industries, partners in projects such as "Transferring Energy Save Laid on Agroindustry"(TESLA) and "Saving COOPerative Energy"(SCOOPE), have very similar annual energy consumption. Specifically, adding the quarter-hourly values for a typical year, they show a consumption of 124 MWh, 107 MWh, 122 MWh, and 109 MWh. The consumption data of these 4 industries have been the subject of a previous study to evaluate the impact of the new energy context on the electricity bill [1].

To eliminate any bias caused by differences in consumption, the values of power and energy demanded every 15 min have been adjusted by a small correction factor. Thus, an overall factor of 0.9292 has been applied to the first industry, 1.0753 to the second, 0.9447 to the third, and 1.0512 to the fourth. As a result, the 4 patterns analyzed have exactly the same annual consumption, 115 MWh, maintaining the energy demand behavior (Figure 3).

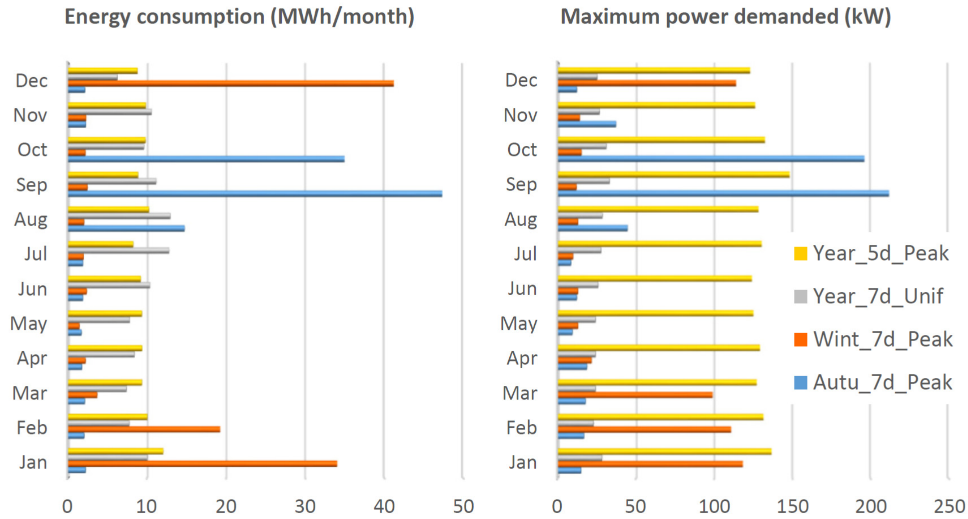

Figure 3. Monthly energy consumption (**left**) and maximum power demanded (**right**) in each of the industries analyzed.

2.4.4. Remaining Parameters

In order to analyze the impact of the size of the PV system, PVs with different peak capacities have been analyzed, from 5 kWp to 100 kWp, with an interval of 5 kWp.

Given the great variation in energy prices, 3 scenarios have been considered. The assumed values are those offered by a marketing company in Spain (Som Energia), specifically:

- Low prices before the energy crisis (June 21): 0.135, 0.119, 0.099, 0.085, 0.073, and 0.069 €/kWh for each of the 6 existing tariff periods.
- Maximum prices reached during the energy crisis (February 22): 0.34, 0.31, 0.291, 0.267, 0.243, and 0.231 €/kWh.
- Intermediate prices close to those in force in 2023, calculated as the average of the 2 previous scenarios: 0.238, 0.215, 0.195, 0.176, 0.158, and 0.150 €/kWh.

To simplify the analyses carried out, the same price has been assumed for the power term in the three scenarios: 24.732, 21.529, 12.320, 9.897, 2.834, 1.571, and 72.884 €/kW year.

The sale of excess energy presents great differences and legal nuances even within the same country. For example, there may be unavailability of discharge points by the distribution companies, as the nodes of the network are saturated; there may be limitations on compensation for energy consumed in certain periods, etc. In cases where this injected energy is paid, it presents great variations depending on the area, the company, the year, etc. Therefore, both the assumption that injecting into the grid is not allowed and the assumption that a third of the cost of the purchased energy is received for the excess energy will be analyzed (value close to the offer of the last months of the reference company).

This work does not quantify the reduction in greenhouse gases due to the increase in energy supplied that is achieved with inclined structures. If the extra financial benefits by carbon credit were taken into account, the budget available for the structure would be greater than the obtained values.

3. Results and Discussions

In order to analyze the wide causality, scenarios of intermediate values have been taken as a reference framework, carrying out a subsequent sensitivity analysis, specifically, the intermediate value of the energy price (close to the current reality) without injection income and intermediate radiation (PSH 4.0).

3.1. Optimization by Modifying Azimuth and Inclination

3.1.1. Influence of the Uniformity and Seasonality of Demand

The consumption pattern strongly conditions the potential savings of the PV and, as a consequence, the financial viability to optimize the orientation and azimuth of the PV system. In those industries with strong seasonality (Autu_7d_Peak and Wint_7d_Peak), the increase in installed capacity is associated with a rapid reduction in the useful energy used per kWp, for any azimuth (Figure 4). This is due to the increase in excess energy that needs to be injected into the grid or in the worst case, curtailed, due to the impossibility of matching electrical supply and demand. The reduction in energy demand on weekends and the lack of uniformity from Monday to Friday (Year_5d_Peak case) also penalize the performance of the PV when increasing the installed capacity. On the contrary, in the industry with relatively uniform and stable consumption throughout the year (Year_7d_Unif), the increase in installed capacity causes a limited loss of energy used for each kWp until its usual demand is exceeded (considering 25 kW as the calculation base).

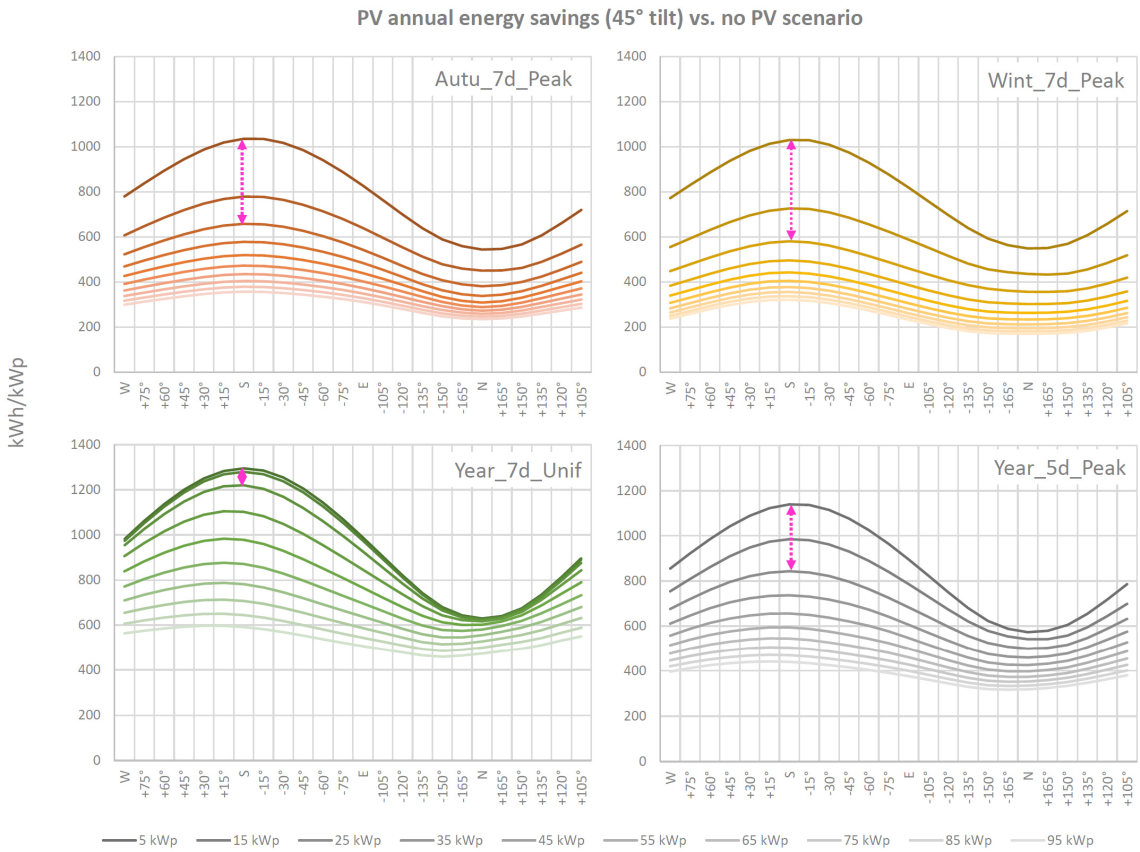

Figure 4. Annual energy savings achieved by a PV installation compared to the scenario without PV, depending on the installed peak capacity and the azimuth of the panel. PV installed with a 45° inclination at the location of 4.0 PSH.

Reduction in the industry's electricity bill is directly linked with the behavior of the energy used, with small differences due to variations in the price of energy and penalties for excess power demanded (Figure 5). Therefore, the greater the seasonality and irregularity of demand, the smaller the differences when changing the azimuth (€/kWp), and therefore, the lower the budget available for an optimization of the PV plane.

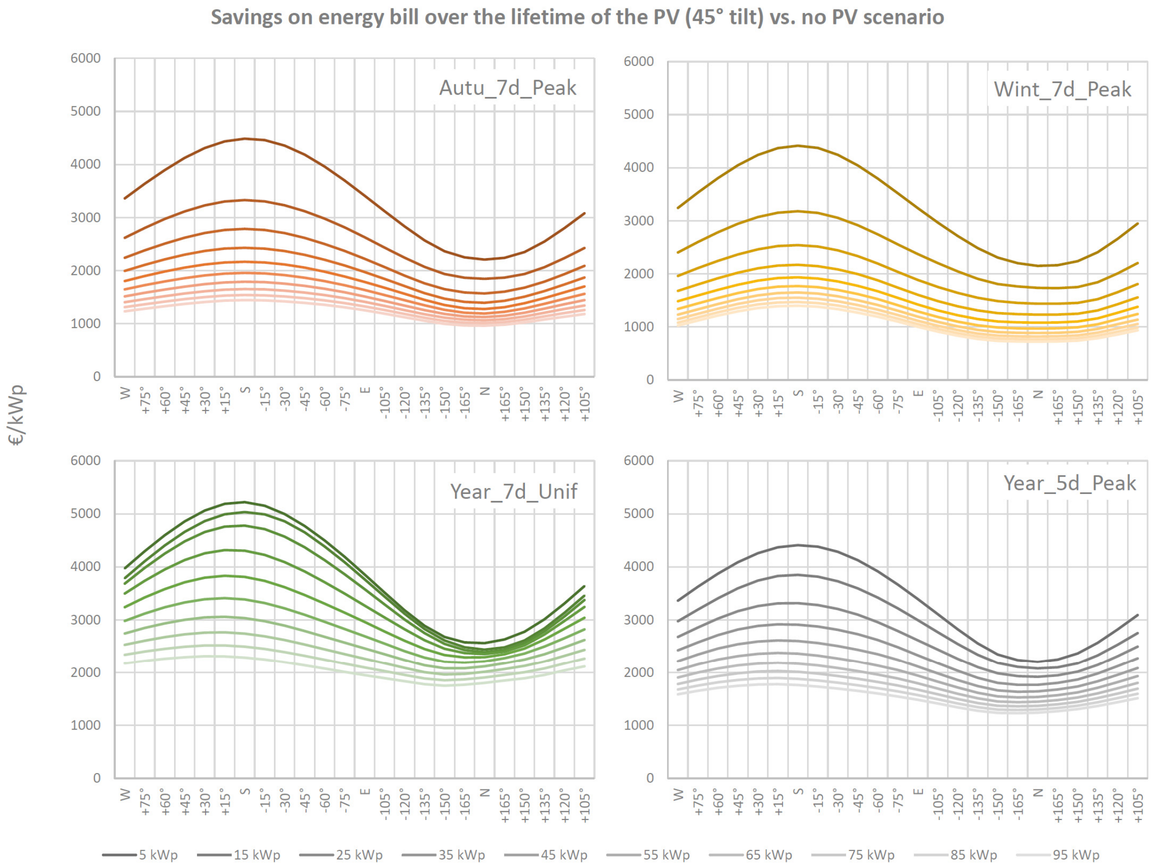

Figure 5. Bill reduction achieved during the lifecycle of a PV installation compared to the scenario without PV, depending on the installed peak capacity and the azimuth of the panel; 45° PV inclination, intermediate energy price, no excess income, and HSP 4.0.

3.1.2. PV with Limited Excess

The suitability of each case has been analyzed through the maximum budget available for the extra cost of an inclined structure that optimizes the plane compared to the budget of a coplanar structure (k€/kWp).

With a small installed capacity where the excesses are reduced (5 kW in the analyzed industries), the consumption pattern has limited importance (Figure 6). In this case, maximum use of the captured energy is ensured, increasing the available margin. Except in cases of azimuth and inclination very close to the optimum, there is a wide budget to optimize the structure. Thus, the average budget of the set of scenarios analyzed for the reference framework is 1.2 ± 0.8 k€/kW in the most unfavorable pattern and 1.5 ± 1.0 k€/kW in the most favorable one. On flat roofs, the wide margin for the extra cost of the structure, between 0.6 and 07 k€/kW, supports the use of inclined structures in all cases. On vertical sawtooth roofs, the budget starts at 1.1–1.4 k€/kW for south orientation, increasing as the azimuth varies, as long as shading can be avoided. Considering only azimuths between 90° and −90°, the margin for the structure is reduced to averages between 0.7 ± 0.5 k€/kW and 0.9 ± 0.7 k€/kW.

Assuming an extra cost of the inclined structure of 0.2 k€/kWp compared to the coplanar one, in 92–94% of the cases, the structure would be amortized over the lifetime of the PV (between 85% and 89% for azimuths between 90° and −90°). The average payback of the different patterns ranges between 4.6 ± 5.0 and 5.5 ± 5.4 years. Scenarios with a payback of fewer than 5 years range between 63% in the most unfavorable pattern and 70% in the uniform pattern. This percentage is reduced to 42–50% with azimuths between 90° and −90°.

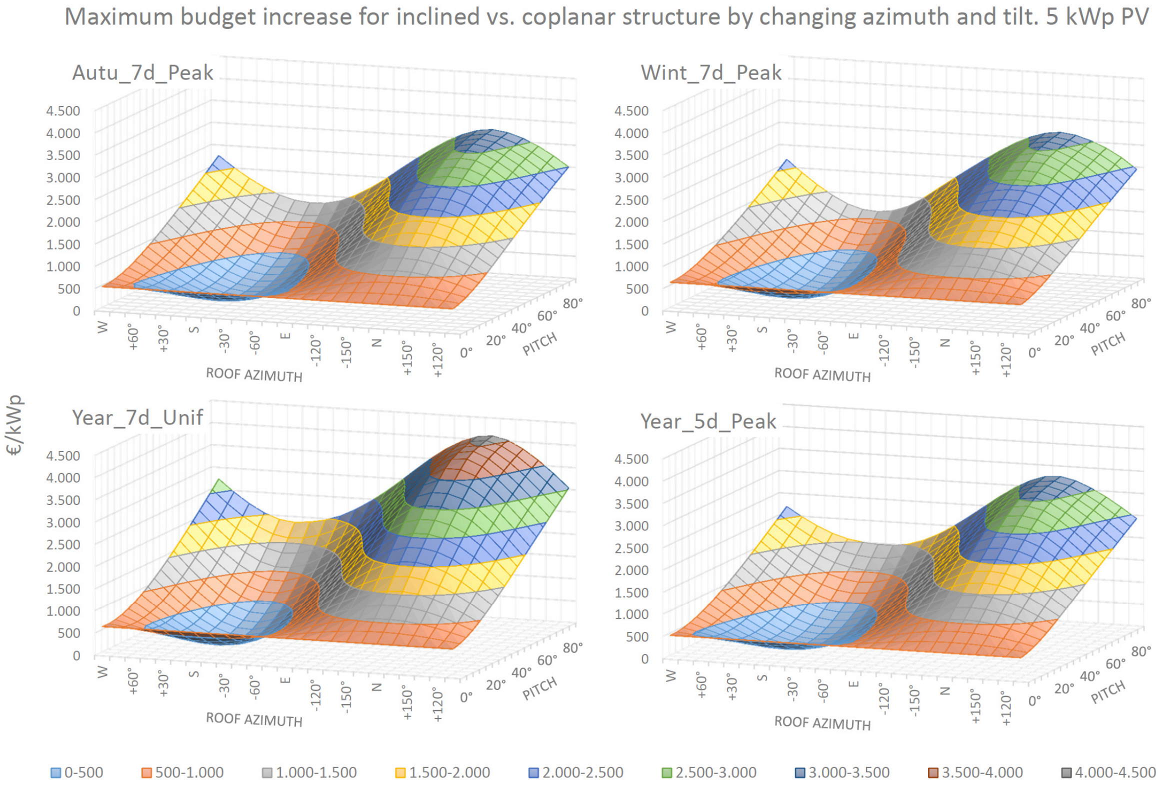

Figure 6. Maximum budget for the extra cost of a structure that changes the orientation and inclination to the optimal case, compared to the cost of the coplanar option; 5 kWp PV, intermediate energy price, PSH 4.0, and no excess income.

However, a low installed capacity leads to a limited reduction in the electricity bill, giving up the potential benefits of an optimized sizing PV system. In the most favorable cases where 5 kWp is installed, the PV would achieve a reduction in the industry's annual consumption of 6–7 MWh compared to the scenario without PV, just 5% of the total (115 MWh).

3.1.3. PV Designed to Increase Savings on the Energy Bill

The increase in installed peak capacity, seeking to maximize the industry's savings, leads to a reduction in the available budget for the extra cost of an inclined structure compared to a coplanar one. This reduction is more pronounced the greater the seasonality and irregularity of demand (Figure 7). Thus, for example, in the industry with the most uniform and constant pattern, the increase in installed capacity to 25 kWp (close to the maximum recorded in it) hardly produces variations in the available budget for the extra cost of the structure, with an average of 1.3 ± 0.9 k€/kW. On the contrary, in the other three patterns, there is a drastic cut, with an average of 0.6 ± 0.4 k€/kW, 0.6 ± 0.5 k€/kW, and 0.8 ± 0.6 k€/kW for Wint_7d_Peak, Autu_7d_Peak, and Year_5d_Peak, respectively. Considering azimuths between 90° and −90°, these values would fall to 0.8 ± 0.6 k€/kW and 0.4 ± 0.3 k€/kW. In the most unfavorable pattern, the budget for the extra cost of the inclined structure is reduced to 0.25 €/kWp on flat roofs.

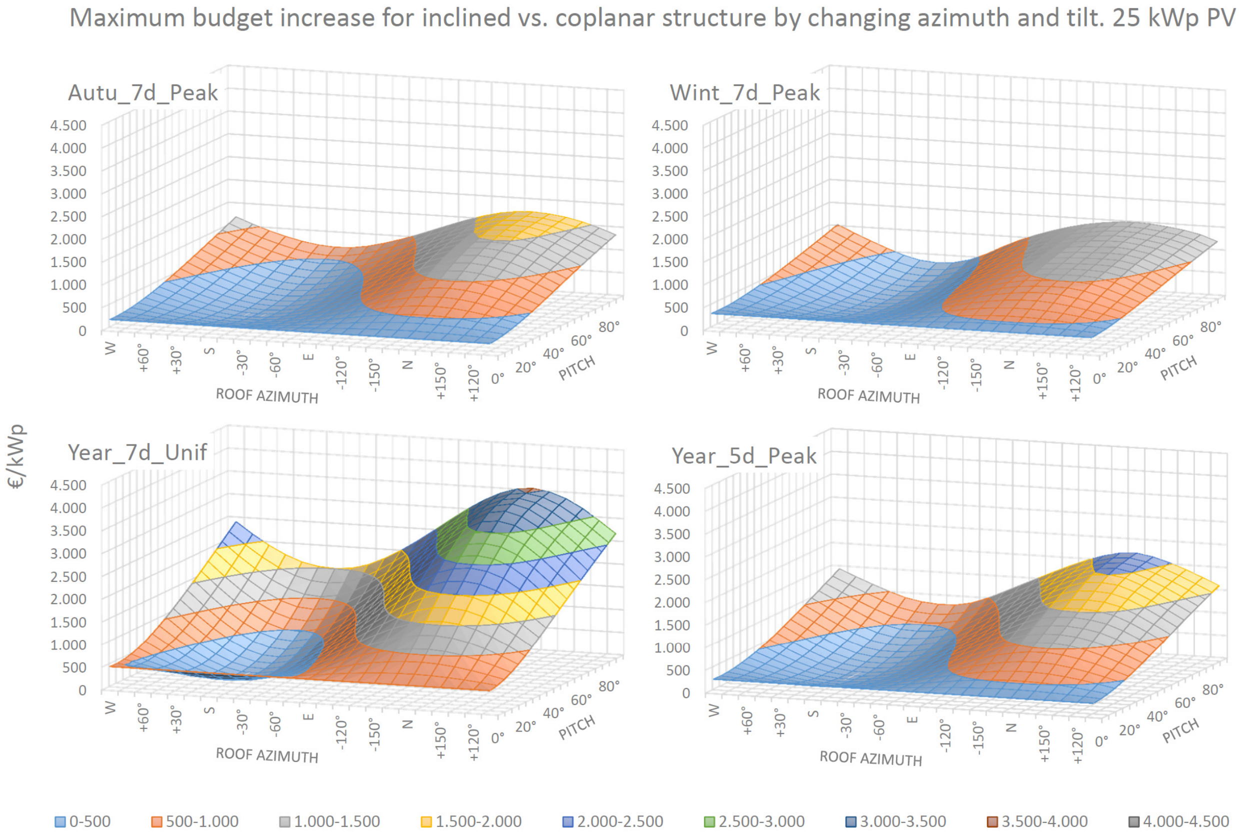

Figure 7. Maximum budget for the extra cost of a structure that changes the orientation and inclination to the optimal case, compared to the cost of the coplanar option; 25 kWp PV, intermediate energy price, PSH 4.0, and no excess income.

The percentage of cases in which the inclined structure would be amortized (cost of the structure of 0.2 k€/kWp) would remain almost the same in the uniform pattern but would drop between 83% and 86% in the other more irregular patterns (67–74% between east and west), with a high number of cases below 0.3 k€/kWp. The payback increases several years in the most irregular patterns, with averages between 8.1 ± 6.3 and 9.3 ± 6.6 years. In the uniform pattern, the increase is more moderate, with an average payback of 5.4 ± 5.4 (an increase of less than one year). Scenarios with a payback of fewer than 5 years would be reduced to 39–65% (11–44% between 90° and −90°).

Therefore, in seasonal and/or irregular consumption patterns, the suitability against the coplanar structure loses strength in a large number of scenarios around the optimal case. On the contrary, in an industry with seasonal and uniform consumption, the increase in installed capacity to a value close to its maximum demand hardly reduces the available budget and the profitability of the inclined structure.

The analyzed scenario of 25 kWp would imply a reduction in annual consumption close to 16 MWh in the most seasonal patterns and 31 MWh in the uniform one, which represents percentages of 14% and 27% of the total consumption (115 MWh). The increase in installed peak capacity to further reduce the bill would lead to greater reductions in the available budget for the structure

3.2. Optimization by Modifying Only the Inclination (Same Azimuth)

The suitability of each case has been analyzed through the maximum budget available for the extra cost of an inclined structure that optimizes the panel's inclination compared to the budget of a coplanar structure (k€/kWp), maintaining the azimuth.

The option to change only the inclination, using structures with the base of the panels parallel to the ridge of the roof, further reduces the available budget compared to the coplanar option (Figures 8 and 9). In the case of a low-capacity PV system (5 kWp) with reduced excesses, the average budget of the set of scenarios analyzed for the reference framework falls to 1.0 ± 0.9 k€/kW in the most favorable pattern and values close to 0.8 ± 0.8 k€/kW in the other three (Figure 8). Considering only azimuths between 90° and −90°, the margin for the structure is much smaller, with averages between 0.4 ± 0.4 k€/kW and 0.6 ± 0.6 k€/kW.

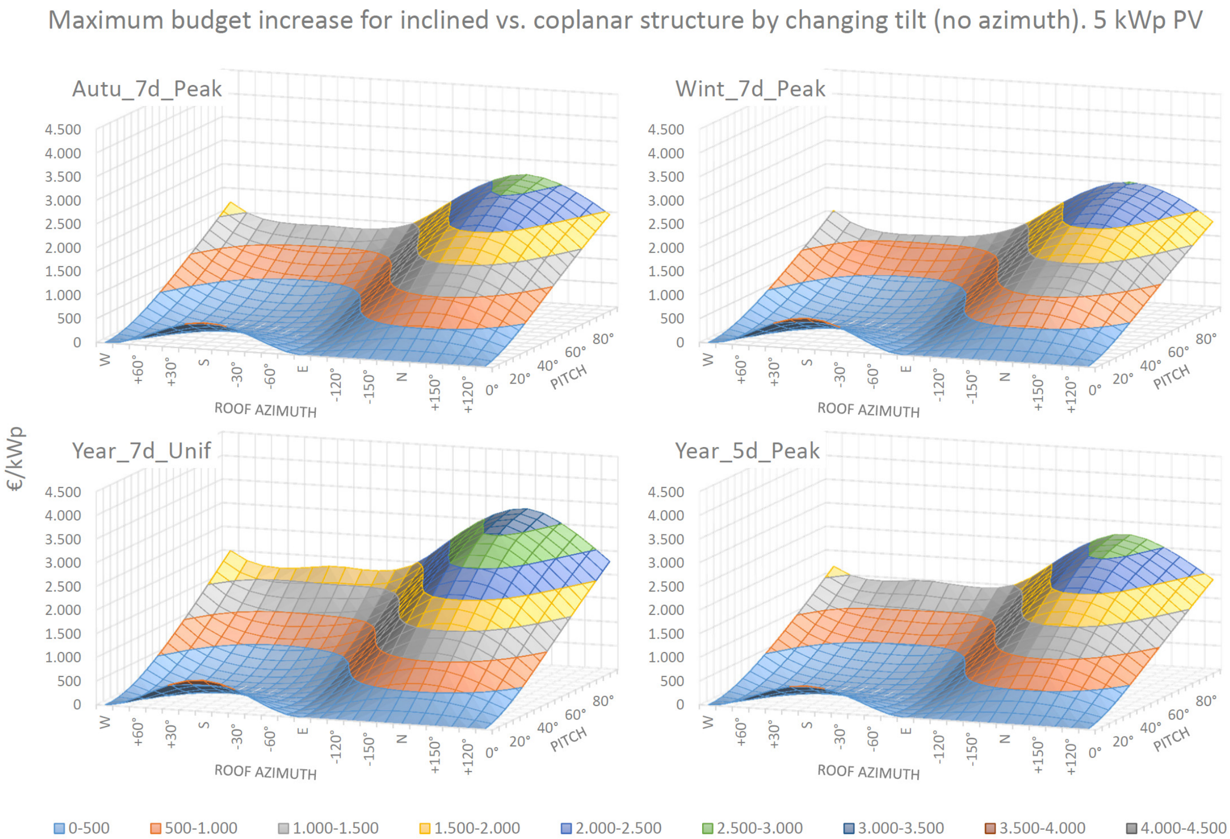

Figure 8. The maximum available budget for the extra cost of a structure that achieves the optimal inclination (but not the azimuth), compared to the coplanar option; 5 kWp PV, intermediate energy price, PSH 4.0, and no excess income.

Assuming the same extra cost of the inclined structure (0.2 k€/kWp), the percentage of cases in which the structure would be amortized in 20 years is reduced to 70–74% of the analyzed cases (between 56% and 62% for azimuths between 90° and −90°). The payback of the different patterns would increase to averages between 8.5 ± 7.7 and 9.7 ± 7.6 years. Scenarios with a payback of fewer than 5 years would fall to 41% in the most unfavorable pattern and 52% in the uniform pattern (23–34% with azimuths between 90° and −90°).

When increasing the installed capacity to 25 kWp, the differences between the irregular patterns and the uniform pattern increase (Figure 9). The average threshold budget is 0.3 ± 0.3 k€/kW for the winter seasonal pattern, 0.5 ± 0.4 k€/kW for the autumn one, 0.5 ± 0.5 k€/kW for the weekday one, and 0.9 ± 0.9 k€/kW for the uniform one. Limiting the scenarios to azimuths between east and west, these values are reduced to 0.2 ± 0.2 k€/kW, 0.2 ± 0.2 k€/kW, 0.3 ± 0.3 k€/kW, and 0.5 ± 0.5 k€/kW.

Assuming an additional cost of the inclined structure of 0.2 k€/kWp compared to the coplanar one, the percentage of cases in which the structure would be amortized in 20 years is reduced to 53–72% of the cases analyzed (between 31% and 60% for azimuths between 90° and −90°). The payback of the different patterns would increase to averages between 9.0 ± 7.7 and 13.7 ± 6.8 years. Scenarios with a payback of fewer than 5 years remain around 50% in the most favorable pattern but fall to 18–27% in the rest. Considering azimuths between 90° and −90°, in the winter pattern, no case presents a payback of fewer than 5 years.

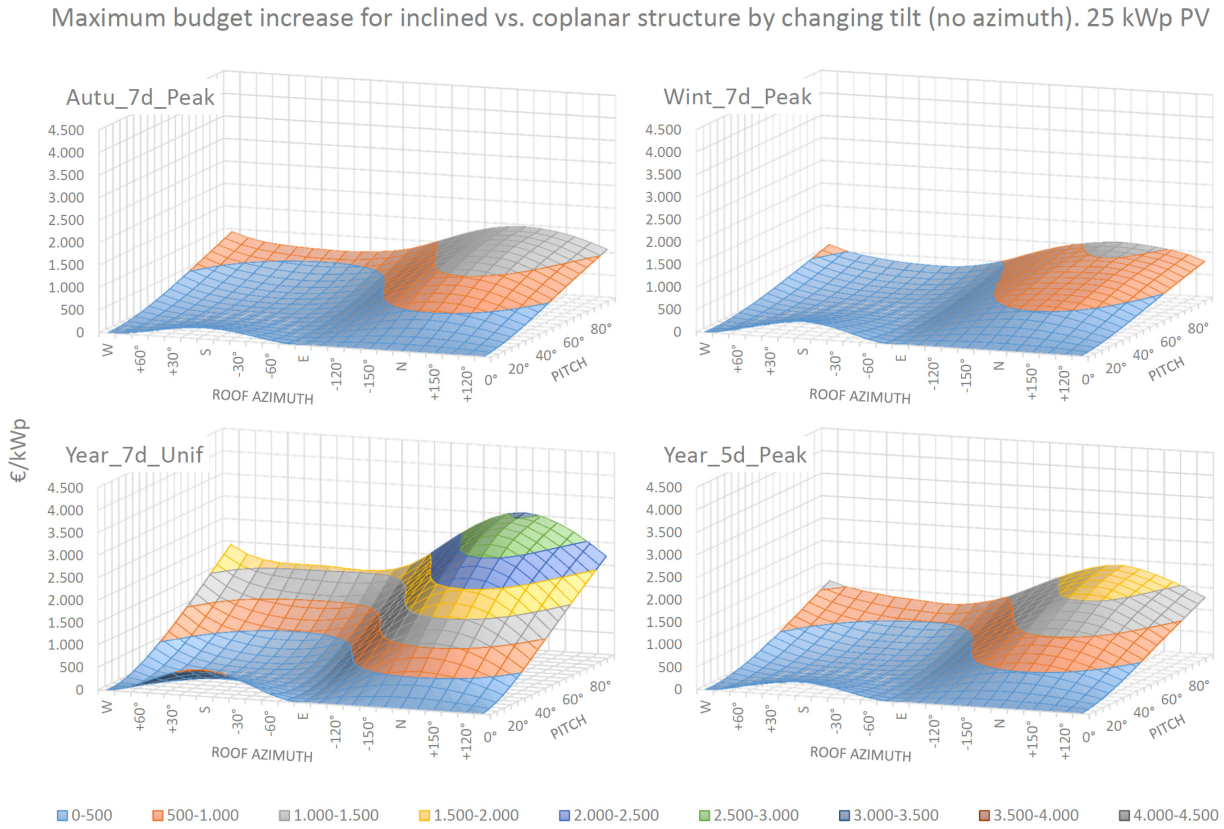

Figure 9. Maximum budget available for the additional cost of a structure that achieves the optimal inclination (but not the azimuth), compared to the coplanar option; PV of 25 kWp, intermediate energy price, PSH 4.0, and no excess income.

Therefore, in irregular and/or seasonal consumption patterns, when seeking to maximize energy bill savings (with associated energy excesses), the design of structures by modifying only the inclination presents disadvantages compared to azimuth optimization.

3.3. Sensitivity Analysis

The maximum budgets available for an inclined structure compared to the coplanar one experience significant variations when modifying the values assumed in the reference framework. Table 1 summarizes the variations of the global average compared to the reference framework, both in the case of optimization with azimuth and inclination and in the case of only inclination.

Table 1. Average variation in the maximum available budget (k€/kWp) compared to the reference framework (PSH 4.0, without income from energy surpluses, and intermediate energy price).

Peak Capacity	**Energy Price**	**Excess Income**	**Azimuth and Inclination**						**Inclination**					
			PSH 3.0		**PSH 4.0**		**PSH 5.0**		**PSH 3.0**		**PSH 4.0**		**PSH 5.0**	
			ẋ	**σ**	**ẋ**	**σ**	**ẋ**	**σ**	**ẋ**	**σ**	**ẋ**	**σ**	**ẋ**	**σ**
5 kWp	High	X	0.0	0.1	0.6	0.4	1.2	0.9	0.0	0.0	0.4	0.4	0.8	0.8
		√	0.1	0.1	0.7	0.5	1.5	1.0	0.1	0.1	0.5	0.5	1.0	0.9
	Med.	X	−0.4	0.3	0.0	0.0	0.5	0.4	−0.3	0.2	0.0	0.0	0.3	0.3
		√	−0.3	0.2	0.1	0.1	0.6	0.5	−0.2	0.2	0.1	0.1	0.4	0.4
	Low	X	−0.8	0.6	−0.6	0.4	−0.4	0.3	−0.5	0.5	−0.4	0.4	−0.2	0.3
		√	−0.8	0.6	−0.5	0.4	−0.3	0.3	−0.5	0.5	−0.4	0.4	−0.2	0.2

Table 1. *Cont.*

Peak Capacity	Energy Price	Excess Income	Azimuth and Inclination						Inclination					
			PSH 3.0		PSH 4.0		PSH 5.0		PSH 3.0		PSH 4.0		PSH 5.0	
			ẋ	σ	ẋ	σ	ẋ	σ	ẋ	σ	ẋ	σ	ẋ	σ
25 kWp	High	X	0.0	0.1	0.4	0.3	0.8	0.7	0.0	0.1	0.3	0.3	0.5	0.6
		√	0.3	0.2	0.8	0.5	1.3	0.9	0.2	0.2	0.5	0.5	0.9	0.8
	Med.	X	−0.3	0.2	0.0	0.0	0.3	0.3	−0.2	0.2	0.0	0.0	0.2	0.2
		√	−0.1	0.2	0.3	0.2	0.6	0.5	0.0	0.2	0.2	0.2	0.4	0.4
	Low	X	−0.5	0.4	−0.4	0.3	−0.2	0.3	−0.3	0.4	−0.3	0.3	−0.2	0.2
		√	−0.4	0.4	−0.3	0.3	−0.1	0.3	−0.3	0.4	−0.2	0.3	0.0	0.2

3.3.1. Energy Price

Increasing electricity prices has translated into a substantial change in the viability of structures and subsequently in the collection area. The change in values from 2021 (low price analyzed) to the values of mid-2023 (intermediate price analyzed), if maintained in the future, implies an increase in the budget available for the additional cost of the structures of several hundred euros in large part of the scenarios analyzed (Table 1).

Thus, for example, considering a 5 kW PV in the reference framework, the average budget available for the structure would go from 0.6 ± 0.4–0.8 ± 0.6 k€/kW with low prices prior to the crisis (low price) to 1.2 ± 0.9–1.5 ± 1.0 k€/kW with intermediate prices close to the present. The increase would be much more spectacular if prices in the future stabilized around the maximums recorded during 2022 (1.8 ± 1.3–2.2 ± 1.6 k€/kW).

3.3.2. Radiation Site

Solar radiation is another parameter that leads to significant variations in the budget available for inclined versus coplanar structures. The differences between locations with low irradiation (PSH 3.0) and high irradiation (PSH 5.0) can mean variations in the average budget of more than 1 k€/kWp, especially with high energy prices (Table 1). Thus, for example, in the case of a 5 kW system and intermediate energy price, the average for the budget would go from 0.8 ± 0.6–1.1 ± 0.7 k€/kW for PSH 3.0 to 1.6 ± 1.2–2.0 ± 1.4 k€/kW for PSH 5.0. Considering azimuths between 90° and −90°, they would go from 0.5 ± 0.4–0.6 ± 0.5 k€/kW (PSH 3.0) to 1.0 ± 0.7–1.3 ± 0.9 k€/kW (PSH 5.0).

3.3.3. Optimization with Income from Surplus Energy Injected into the Grid

The possibility of being paid for the electricity injected into the grid reduces the differences between consumption patterns as the PV capacity increases. For example, with a 25 kWp PV system in the reference framework, assuming income for each kWh injected into the grid of 1/3 of the price of the energy purchased, the average budget for the structure would increase from 0.6 ± 0.4 k€/kW without income to 1.0 ± 0.7 k€/kW with income for the most seasonal patterns (Wint_7d_Peak and Autu_7d_Peak). Considering azimuths between 90° and −90°, such levels would go from 0.4 ± 0.3 to 0.6 ± 0.4 k€/kW.

In all cases, income from electricity injected into the grid improves results, ensuring a higher profitability of the installation. However, its importance is limited to low energy prices, even in cases where the installed capacity is high (Table 1). On the contrary, with high energy prices, such a scenario allows increasing the maximum budget by several hundred euros.

4. Conclusions

The industry consumption pattern is a key factor in ensuring the viability and profitability of any mounting structures of solar photovoltaic installations. In industries with a seasonal and/or irregular consumption pattern, the increase in installed peak capacity, with the aim of maximizing savings on the energy bill, leads to a significant reduction in the available mounting budget for inclined structures compared to the coplanar option. Thus, for example, with a strongly seasonal pattern, going from a reduction in annual consumption of 4% to 16% leads to a halving of the mounting budget; in an industry with relatively uniform consumption, going from 5% to 31% barely implies a reduction of 15% of the budget.

Depending on the azimuth and inclination of the industry's rooftop, the maximum budget available for an inclined mounting structure that optimizes the collection plane can vary by more than a thousand euros per kWp. The further the azimuth and inclination move from the optimal values, the higher the available budget will be; therefore, it is especially profitable in orientations close to the east and west and in roofs partially inclined to the north, as long as the panels are arranged avoiding shading. For example, with a PV designed to increase savings on the energy bill (installed capacity of 25 kW) and assuming intermediate energy prices and radiation, the average budget for optimizing the system on a west-facing roof (considering all the inclinations) was 1.3 k€/kWp for the uniform consumption pattern and 0.7 k€/kWp for the seasonal and/or irregular consumption pattern.

The design of structures by modifying only the inclination presents disadvantages compared to azimuth optimization, especially in irregular and/or seasonal consumption patterns. In the previous example (optimizing the west-facing roof), the mean budget was reduced to 0.8 k€/kWp (uniform consumption pattern) and 0.4 k€/kWp (seasonal patterns). The cost of the mounting structure would have to differ little from the coplanar option and be less than that of azimuth-modifying structures to make the choice worthwhile.

In the last 2 years, the increase in electricity prices has led to a substantial change in the viability and profitability of structures optimized for the plane compared to the coplanar option. If the prices at the beginning of 2023 are maintained in the future, the budget available for the structures would increase by several hundred euros compared to the prices in mid-2021, modifying accepted design paradigms until now. In the example of optimizing a west orientation, the budget would be halved considering pre-crisis prices and would almost double if the prices were increased to crisis highs.

The differences between locations with low irradiation and high irradiation can mean variations in the average budget of more than 1 k€/kWp, especially with high energy prices. The average budget doubles from 3.0 HSP to 5.0 HSP.

The possibility of selling electricity injected into the grid reduces the differences between consumption patterns. In the previous example (optimizing the west-facing roof), the mean budget was increased to 1.4 k€/kWp for the uniform consumption pattern and 1.0 k€/kWp for the seasonal patterns. However, its importance is limited to low electricity prices, even in cases where the installed capacity is high.

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