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Shifting Angles, Shifting Revenues: An Assessment of the Optimal PV Azimuth

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Abstract. The significant reduction in the production costs of photovoltaic energy is leading to a rapid increase in the number of new facilities connected to the grid, with fixed systems currently being the most frequent. Until now, facilities have been designed to obtain the maximum amount of energy but, as the production is concentrated in the central hours of the day, the expansion of supply in these hours causes a significant reduction in prices, becoming zero or negative, which would compromise the economic sustainability of these facilities. To avoid or at least reduce this price cannibalization effect, this paper proposes a method that seeks to identify the azimuth angles that maximize the revenue of a PV plant. This is applied to a specific location in southern Spain, using prices from 2016 to 2024. The evolution of the optimal configuration throughout this period is examined and possible long-term trends discussed.

Key words. Optimal PV, azimuth angles, Maximum PV revenue, price cannibalization, price duck curves.

1. Introduction

Photovoltaic generation capacity is globally increasing over three times faster than wind capacity. In fact, in 2023, solar PV accounted for three-quarters of renewable capacity additions worldwide [1].

Unlike in the past, when panels were very expensive and two-axis tracking systems were commonplace, many PV plants are nowadays fixed, the optimal panel orientation (tilt angle) being determined beforehand to maximize the energy yield for a given latitude [2] [3]. This has been the subject of research in the last decade. For instance, in [4] the main objective was to maximize the annual energy production, considering a correlation factor for the tilt angle, the site latitude and the climatic conditions. Several cities in France and Italy were considered. Other studies, such as [5], have similar aims but focus on different regions (e.g., some provinces in Turkey). Details of the calculations to maximize production can be found in [6]. Other factors affecting the production of PV panels, e.g. cell temperatures and dust accumulation, have been also analyzed [7] [8], [9].

To a lesser extent, some studies have focused on the impact of solar panel orientation on production revenues. Reference [10] concluded that the orientation of PV systems can change if other objectives, e.g. maximizing revenue from the sale of surplus energy, are considered. Depending on the price behavior, higher profits can be achieved with different configurations. Similarly, [11] indicated that electricity prices should be considered when assessing the profitability of PV panels. Revenues are not very sensitive to moderate changes in orientation, as more than 95% of the maximum available revenues are obtained over a wide range of orientations. However, revenues from an east-west orientation can be up to 15% lower than that of an optimally oriented system. In [12], the Negev region of southern Israel was used as a case study. The results pointed out that each site should be studied separately by duly considering both meteorological conditions and feed-in tariffs, as the optimal orientation to maximize energy does not always coincide with the optimal orientation to maximize revenue.

In [13], three strategies were proposed to manage the energy production of solar panels and to evaluate the impact on revenues. The objective was to maximize either the capacity factor or yearly revenues over a single year. The mentioned strategies were utilization of 1-axis tracking, curtailment during negative-price hours, and modification of fixed-tilt array orientation. The results showed that for the different energy markets (day ahead and real-time) the azimuth and tilt angle configurations maximizing the revenues are different. Also in this study, curtailment and 1-axis tracking were decided as the most feasible options since the tilt and azimuth angles are determined at the panel installation stage.

A different approach is taken in [14], where an energy community based on PV production is analyzed. The purpose is to find out which tilt and azimuth angles maximize self-consumed energy. Although they consider that the tilt has little influence, there are advantages in the east and west position, in contrast to the south, which provides the greatest amount of energy.

Indeed, in the early days of PV deployment, over a decade ago, when the main source of investment recovery was feed-in tariffs, the optimal orientation of PV panels was the one maximizing the energy yield. This is also the case if the plant owner signs a lump sum power purchase agreement (PPA) with a consumer.

However, in the last few years, the cost of PV panels has drastically decreased (over 95% in a decade) and most regulatory systems require that PV plants, much like wind farms did before, trade their production in day-ahead markets. While many of those markets, e.g. the so-called Price Coupling of Regions (PCR) in Europe, had been relatively stable and predictable before the pandemics, a combination of factors in recent years (gas price spikes owing to the Ukraine war, higher inflation rates, lower demand, etc.) has led to an increased price volatility in short-term markets. Moreover, the high penetration of renewable energy, particularly PV, has led to overproduction and even curtailments during peak solar hours, which is in turn leading to very low or even null prices for many hours a year.

For instance, on 2024, the Iberian day-ahead market has registered null or negative prices for a record of 784 hours (9%), over three times as much as in the past decade [15], threatening the economics of existing PV plants and chasing away investments in most needed new projects. An economic analysis of investments in PV plants in various European countries, considering the levelized cost of electricity (LCOE), has been carried out in [16].

This phenomenon (so-called price cannibalization) is expected to increase over time. For this reason, stakeholders are quickly turning their eyes to energy storage. However, energy storage is either still costly (e.g. battery storage) or involves a very long commissioning time (e.g. pumped hydro). Hence, significant intra-day price differences between central sunny hours and the rest of the day are expected to persist for many years to come.

The goal of this work is twofold: firstly, to conceptually develop a straightforward methodology to determine, for a specific location, the azimuth angles that maximize the annual revenue of a fixed-angle PV system that sells its electricity to the day-ahead market; secondly, to apply the methodology to the case of a PV plant in the South of Spain, in order to analyze the evolution of the prices of the last decade.

The rest of the paper is organized as follows: Section II presents the methodology used to determine the azimuth angle that maximize the revenues of a PV plant; Section III discusses the results of the case study, paying attention to atypical years in the last decade; finally, Section IV summarizes the main conclusions of this work.

2. Orientation for maximum revenues

For a given latitude, open access tools, such as PVGIS [17], provide the hourly production per unit of installed power throughout the year. The tilt and azimuth angles of the panels maximizing the energy yield can be determined automatically by PVGIS, but they can also be freely selected by the user keeping in mind other constraints or goals, as in this work. When the hourly production is multiplied by the hourly wholesale price, and the result is added for all the hours of a year, the total annual income is obtained per unit of installed power. This flow of data is shown in Figure 1.

For given electricity prices, different panel orientations will provide different annual revenues. To obtain the optimal orientation that maximizes revenue, an optimization problem could be formulated mathematically. However, since there is only one degree of freedom (azimuth angle), and the search space (number of combinations) is relatively limited, the optimal combination of panel angles can be more easily determined by fully analyzing all reasonable combinations for every year considered (i.e., by limiting the search space to the range of angles that makes sense for the given latitude). Figure 2 provides the pseudocode that performs this task, assuming that the arrays of hourly production and prices are duly aligned, which entails correcting the PVGIS data to account for daylight saving times (from end of March to end of October in Europe).

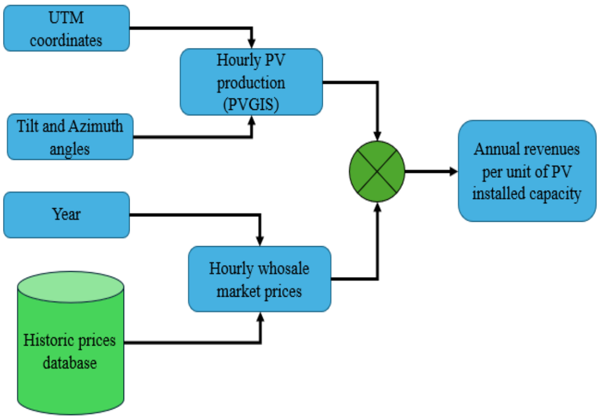

Fig. 1. Determination of annual revenues for a given year and PV panel orientation.

```
Income(Y)=0;
Fix tilt angle(T=34)
 For every hourly vector of prices (Y=P2016, P2017, .... P2024)
  For every azimuth angle (A=-30, -29, ..., 0, 1, 2, ... 29, 30)
   Hourly energy_production(T=34,A)
   Inconme(Y,T,A)= hourly energy_production * hourly vector of prices
     Obtain the annual income, Income(Y,T,A), by applying the procedure of Figure 1
   end
  end
 For every year (X= 2016, 2017, 2017, ... P2024)
   Max_Income(X) =Max ( Income(Y,T=34,A) )
   Save Max_Income(X), T_opt=34 and A_opt(X)
end
```

Fig. 1. Pseudocode to determine the optimal panel orientation maximizing the annual revenue by exhaustive search.

The orientations for maximum revenue and maximum production may differ, depending on the daily and seasonal evolution of price profiles. As illustrated in Figure 2, the maximum revenue configuration for each year from 2016 to 2024 was determined by multiplying the hourly PV production by the corresponding hourly energy prices for that year. The PV production data was obtained from PVGIS, considering azimuth angles ranging from -30° to 30° in 1-degree increments, while maintaining a fixed tilt angle of 34°. While the azimuth variation will provide intraday energy trading (from the central hours to dawn or dusk, depending on the sign), the tilt variation will do the same at the seasonal level. But it is far from trivial to decide about the optimal combination of angles, unless the price profiles are relatively flat on average, in which case the optimal orientation reduces to that of maximum production.

3. Results

In this work, the city of Seville (Spain) was selected to obtain the hourly photovoltaic production per unit of installed power. The data for this site were provided by the PVGIS-SARAH2 database of PVGIS [16]. Tilt angle equal to 34° and azimuth angles (from -30° East to 30° West) were evaluated with a resolution of 1°. The plant capacity is assumed to be 1 MWp for all simulations. An inclination of 34° was considered because this is the tilt angle that maximizes the electricity yield on a yearly basis at the site studied.

Figure 3 compares the hourly production profiles for a typical day in September, when the PV panels are facing east (-30º), south (1º) and west (+30º). This data was obtained from the PVGIS tool. As expected, the production will increase in the early hours of the day when the panels are facing east, while it will be higher late in the afternoon when facing west, but the overall daily production in both cases is slightly lower than when the panels face south (1º azimuth).

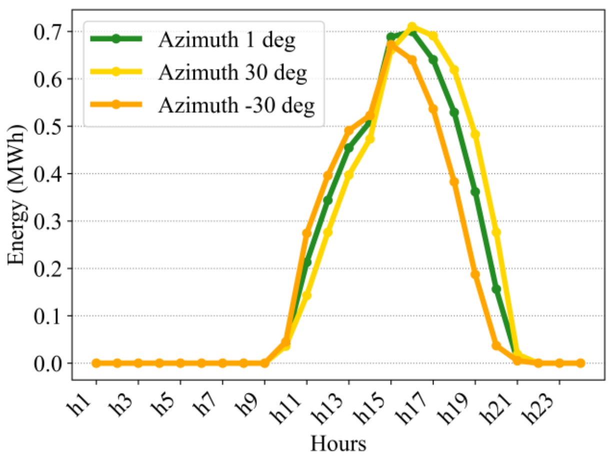

Fig.3. Hourly PV production of 1MWp at Seville 15th September for Azimuth angles facing south, East (-30º) and west (30º).

With the hourly prices of the day-ahead Iberian market, provided by OMIE [15] for the years 2016 to 2024, the annual revenues are obtained following the methodology presented in the former section. As an example, Figure 4 shows the revenues obtained in 2024 by each combination of azimuth and a tilt equal to 34 degrees. It can be observed that the configuration of maximum income is with an azimuth of 8º (red point), while the green point represents the income of the azimuth of higher energy production that 1º.

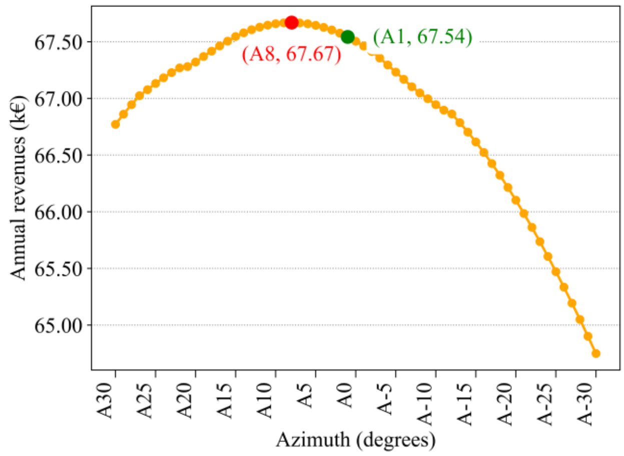

Fig.4. Annual revenues in 2024 as a function of tilt and azimuth angles.

Figure 5 shows the evolution of the azimuth that maximizes the revenues from 2016 to 2024. During the first years, the azimuth is nearly constant around zero degrees. However, in the last years there is a continuous shift to the west, reaching 8 degrees in 2024.

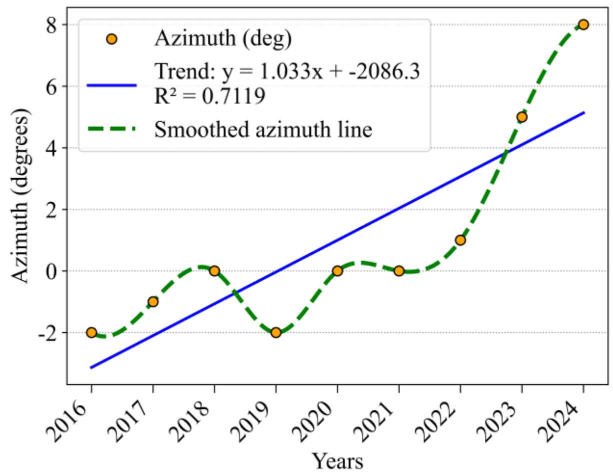

Fig. 5. Evolution of the azimuth angles that maximize the revenues.

To explain the potential reasons of these changes, Figure 6 shows the photovoltaic installed capacity [18], and the evolution of the azimuth angle. This increased capacity is responsible for the price cannibalization therefore, which explains the increased optimal azimuth, in an attempt to increase the revenues late in the afternoon.

While negative azimuth angles (i.e. panels facing to the east) were preferable over five years ago, the current trend suggests larger revenues when facing slightly to the west.

The estimation for the 2030 is 72 GWp of PV installed capacity, according to PNIEC. This is more than twice the current capacity. This is expected to increase the price cannibalization phenomena and the azimuth angle, depending mainly on the amount of storage deployed. As can be seen in Figure 6, if this trend of total photovoltaic capacity installation continues, according to PNIEC we will reach 72GW in 2030, therefore the optimum angle will reach 19 degrees (west) at about, this azimuth value is obtained by using the regression equation presented in Figure 6 where for the 2030 we have that Azimuth (2030) is equal to 0.3144 (72GW) -3.5069 that is 19º.

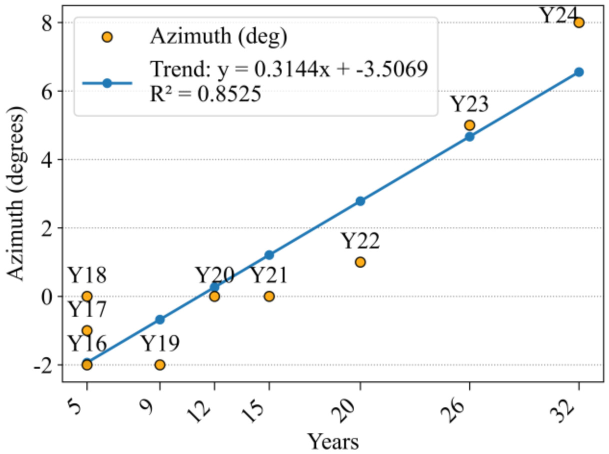

Fig. 6. Evolution of the azimuth angles and PV installed capacity.

4. Discussion

This section analyses the evolution of the azimuth angle from 2016 to 2024 and how the azimuth configurations of current PV installations affect the price of electricity during peak hours, which in turn affects the profitability of investors and the security of the system.

Figure 7 compares the evolution of the hourly average prices at the beginning of the studied period (2016) with those of the last few years after the COVID pandemics. Apart from a general trend for the average prices to increase (from around 40 €/MWh in 2016 to 80 €/MWh in 2023 or 160 €/MWh in 2022), the most noticeable effect, as the years go by, is a significant increase of the price volatility (variance) throughout the day, from the relatively flat prices in 2016 to the "duck"-shaped prices of recent years (i.e., very low or null during daylight hours and higher during peak hours). This is undoubtedly related to the sustained increase of installed PV power in the last five years, after a decade when the installed capacity remained constant, which in turn is leading to the "duck curve" of the net demand, in absence of sufficient storage or other flexibility resources.

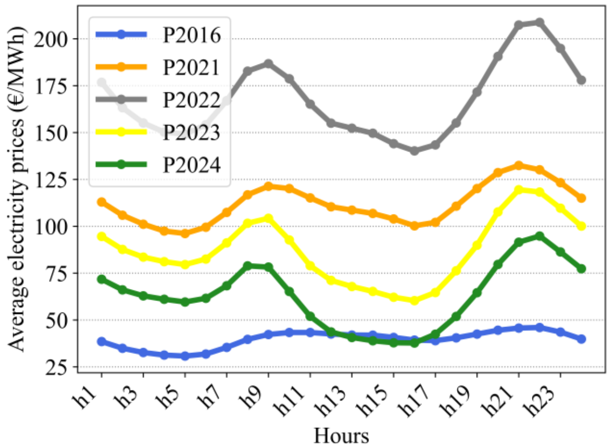

Fig. 7. Hourly average electricity prices between 2016 and 2024.

Figure 8 shows the evolution of average hourly prices for a specific day (June 11, 2024), where the "duck" shape is very apparent. Hours with very low or null prices have been very common throughout 2024 in the Iberian Peninsula market (a total of 784 hours with null or negative prices), owing to a combination of factors (increased wind and hydro production in winter, mild weather and PV production rising since March). Figure 8 also shows the PV production of 1 MWp of PV, both when maximum yield is sought (azimuth angle equal to 1º) and when maximum revenue is the goal (azimuth angle equal to -30º East). Clearly, when looking eastward, the slightly lower daily production is more than offset by higher morning prices (in both cases the tilt angle is assumed to be the one maximizing the production, i.e. 34º).

The optimal azimuth arising for June 11 contrasts with the one obtained if one wants to maximize the income of the last year, which turns out to be 8° West. Indeed, each day has its own optimal orientation, determined by the hourly price evolution and the hourly production of panels with different azimuthal angles (Figure 3), but in the last two years the number of days with higher prices in the late afternoon clearly exceeds the number of days with higher prices in the early morning, which favors westward orientation.

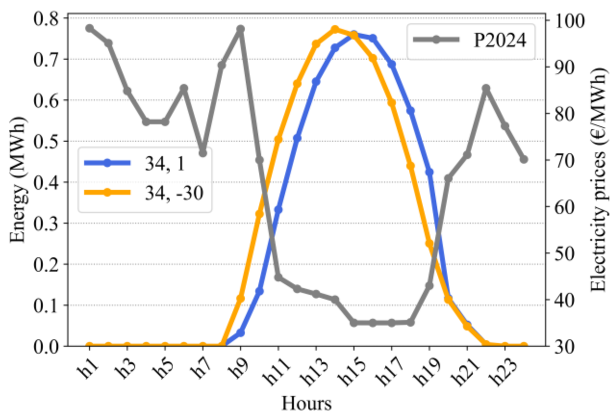

Fig. 8. Hourly prices on June 11, 2024, and PV production for maximum yield and maximum revenue (with tilt 34º).

The lesson learned from this example is that the azimuth angle maximizing revenues is quite volatile daily. On average, when a whole year is considered, the optimal value can hence be rather small. In the future, when more storage is deployed, prices might return to the “normality” of the previous decade (i.e. less daily variance), in which case the azimuth angle maximizing revenues will be very close to the one maximizing electricity yield.

Therefore, to recap, the more stable prices remain during the day, the closer the optimum azimuthal angle is to that of maximum production (1º in Seville). Reciprocally, the closer the price curve approaches the duck shape (i.e., low prices in the middle hours of the day), the more the orientation of maximum revenues will deviate eastward or westward, depending on when peak prices take place (in the morning or in the afternoon).

For the azimuth angle, a moderately significant trend to westward panel orientation is observed in the last three years, even though eastward orientations (i.e., negative azimuths) were more common before 2020 (see Figure. 5). This is clearly due to the increasing cannibalization of prices in the central hours of the day mentioned above, arising from the fast deployment of PV capacity in Spain (which has roughly doubled in the last three years). Statistically, over the past two years, late afternoon prices have tended to be higher than early morning prices, largely in line with demand trends favoring westward orientations. Note, however, that the differences between eastward and westward orientations are not very significant in terms of total incomes, so what really matters is to reduce the production in the central hours of the day, to avoid null or even negative prices.

5. Conclusions

This paper has analyzed the azimuth angles that, for a specific location and expected electricity prices, maximize the revenue of a fixed-angle PV plant that sells its production to the day-ahead pool. The assessment is performed considering the irradiation at the South of Spain (Seville) and the wholesale prices recorded in the Iberian Peninsula in the period 2016-24.

At present, PV power plants have been built for maximum energy configuration (and therefore minimum LCOE), which makes sense if electricity prices are relatively stable. Technological progress, cost evolution and energy structure are causing significant changes in the hourly and seasonal profiles of electricity prices, which are expected to increase in the future if the government's announced plans for the energy transition are fulfilled. The reduction of prices at certain times (cannibalization) justifies an analysis of the configuration of photovoltaic facilities in a revenue-maximizing approach, ensuring their economic sustainability.

From the analysis of the Iberian day-ahead market prices there are no clear seasonal patterns, since they depend on exogenous events (Philomena cold wave, Ukraine war...etc.). We do observe a gradual reduction in energy prices in the central hours of the day, caused by the huge increase in photovoltaic systems, which concentrate their production in these hours. This cannibalization of prices means that the increase in production in the central hours of the day results in little income, so it makes sense to shift the azimuth to the east or west, reducing its energy production, but shifting it to higher-priced hours.

This study introduces future research directions such as the analysis of the estimation of energy prices taking into account the increase of photovoltaic installations by evaluating their different configurations of angles, including the use of storage systems.

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