Analysis on the Optimum Tilt and Azimuth Angles for Fixed-Tilt PV Systems

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Abstract – **The integration of photovoltaics (PV) will impact the future prices of electricity, and with their increased integration expected to lead to a reduction in the demand for traditional power sources, resulting in a decrease in electricity prices. As more PV is used, it is expected that the shape of the daily price of electricity will become much more predictable, with lower prices during the middle of the day and higher prices during the morning and evening. This paper analyses the tilt and azimuth angles that will yield maximum revenue for fixed-tilt PV systems taking into account the electricity prices on the day ahead markets.**

Keywords – **PV systems, Optimal tilt angle, Optimal azimuth angle.**

I. INTRODUCTION

The integration of utility-scale and rooftop mounted PVs is expected to have a significant impact on the operation of power systems [1], the development of electricity markets, and thus, and future prices of electricity [2]. PV systems generate electricity from the sun's energy, which is a renewable and abundant source of power. As the cost of PV systems continues to decrease [3], [4], their use is expected to increase, resulting in a reduction of electricity generation from traditional power sources, such as coal and natural gas. Consequently, the reduced demand for traditional sources of electricity is expected to lead to a decrease in their prices [1]. As the share of PV-generated electricity in the overall energy mix increases, the prices of traditional sources of electricity will need to remain competitive to remain relevant in the market. This competitive pressure is likely to drive down the prices of traditional sources of electricity, resulting in lower overall electricity prices [5].

Furthermore, rooftop mounted PV systems have become an attractive option for consumers to mitigate the effects of the energy crises and the increased electricity prices in the past year. During the warmer parts of the year, these systems are likely to generate excess electricity, which can be fed back into the grid. The effect of such situation may be further decrease of use of traditional sources of electricity and potentially occurrence of negative prices during peak generation periods. This situation is likely to become more frequent as the integration of PV systems continues to increase.

Besides improvement of forecasts to optimize operation and revenues of their systems [6] there are several ways in which PV owners can increase their revenue in those conditions [7]. Nowadays fixed-tilt PV systems are designed to maximize the production throughout the year and various support tools exist to support the process [8]. In this paper a different approach is analyzed considering tilt and azimuth angles that will yield maximum revenue for a certain period.

The paper is organized as follows: the first section gives an introduction to the effect of PV integration on the electricity prices, the second section gives a brief introduction of the factors that affect the electricity prices and the expected shape of the electricity price on the day ahead market (DAM). The next section describes the simulation model for performing the optimization analysis as well as a case study for North Macedonia supported with results and discussion. Lastly, section 4 concludes this paper.

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II. ELECTRICTY PRICES

A. Factors Affecting the Daily Price of Electricity

The hourly electricity price of electricity is affected by various factors, including demand, supply, weather conditions, and government policies. The demand for electricity tends to be highest during certain times of the day, such as in the morning and evening when people are waking up or coming home from work. The supply of electricity is dependent on the availability of power plants and the cost of fuel. Weather conditions also play a role in the daily price of electricity, particularly in areas where the use of renewable energy sources is prevalent. For example, wind turbines generate more electricity on windy days, while solar panels generate more electricity on sunny days. Government policies can also affect the daily price of electricity, particularly policies related to taxes and subsidies [2] [9].

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B. Impact of Renewable Energy Sources on the Daily Price of Electricity

The shape of the hourly electricity price of electricity is likely to change significantly as the use of solar power increases [3]. Currently, the shape of the hourly price of electricity tends to be highly variable, with prices spiking during periods of high demand and dropping during periods of low demand. As more and more solar power is used, it is expected that the shape of the hourly price of electricity will become much more predictable, with a consistent pattern of low prices during the middle of the day when solar power is abundant and higher prices during the morning and evening when solar power production is low [4], as shown on Fig 1. The presented example refers to the day ahead market (DAM) prices on the Hungarian power exchange (HUPX) on 25th of March, 2023 and it clearly shows the price valley that occurred during mid-day hours. Fig 1 [14] presents the day ahead market (DAM) prices on the Hungarian power exchange (HUPX) on 25th of March, 2023 and it clearly show the price valley that occurred during mid-day hours. As solar power production increases during the middle of the day, the supply of energy will exceed the electricity demand, leading to a surplus of electricity in the grid. Consequently, the prices of electricity will decrease. This phenomenon is often referred as valley, where electricity prices dip significantly during mid-day hours due to the surplus of energy generated by PVs. As the integration of PVs is expected to increase, the number of days on which price valleys will occur is also expected to increase.

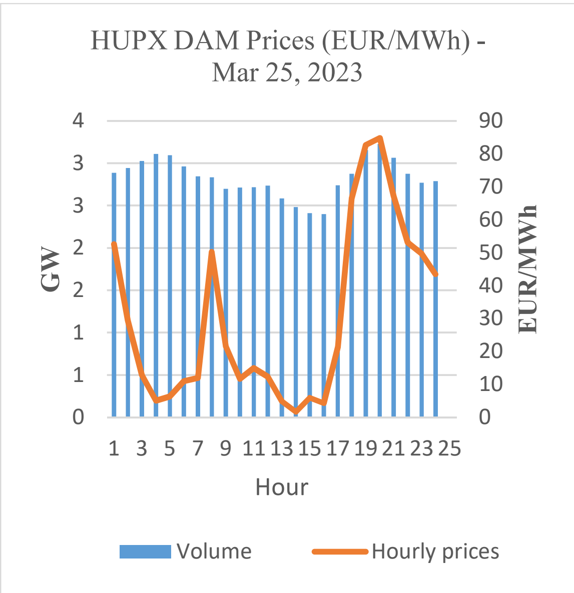

Fig. 1. HUPX DAM Prices on March 25, 2023

The shift towards a more predictable pattern of electricity prices will have several implications for both consumers and producers. For consumers, the predictability of electricity prices will make it easier to plan energy usage and adjust consumption patterns. On the other hand, PV owners, who sell their excess electricity to the market, will receive a lower price for their excess electricity [5]. This can result in a reduction in the value of solar energy and discourage investment in PV systems.

To address these issues, the existing regulatory options may be explored - the use of feed-in premiums to support the small PV generating systems, as well as implementing various dynamic tariff options to transfer demand in certain periods of the day. Additional measures can be taken by the PV owners, such as installation of energy storage systems (ESS), installation of solar tracking systems or changing the tilt and azimuth angle of fixed-tilt PVs to values that maximize the profit. The latter approach suggests that the values of the tilt and azimuth angles that maximize the production of the PV system may not be the same as those that maximize the profit.

III. CASE STUDY

C. Modelling

In order to calculate the tilt and azimuth angles that will maximize the production and profit of a PV system, a simulation model was created using the Python programming language (version 3.8). The model includes several sub-modules for simulating the performances of a PV system:

- Solar position calculations;
- Atmospheric transmission and refraction calculations;
- Irradiance modeling;
- Temperature modeling;
- Single-diode model.

Solar position calculations sub-module determinates the angle of incidence (AOI) of the direct irradiance to the module's surface defined in [6]. The Atmospheric transmission and refraction calculations sub-module is used to model the effects of atmospheric conditions on the incoming solar radiation that reaches a PV module or system such as absorption, scattering and refraction. This sub-module is based on the analytic model described in [7]. The Irradiance modeling sub-module includes functions for calculating the direct, diffuse, and reflected components of solar radiation, based on the sun's position, the time of day and year, and the atmospheric conditions as described in [8]. The Temperature modeling sub-module includes functions for calculating the temperature of a PV module or system based on the ambient air temperature, the irradiance, and the wind speed based on [9]. The Single-diode sub-module includes functions for calculating the I-V characteristics of a PV device based on the single-diode model [10], as well as functions for estimating the parameters of the single-diode model from experimental data [11]. The module can be used to predict the electrical output of a PV module or system under different operating conditions, such as varying irradiance and temperature levels.

In order to calculate the optimal tilt and azimuth angles that maximize the profit of the PV system on one hand and the power produced by the PV system on the other hand, the Sequential Least Squares Programming optimizer (SLSQP) implemented in the scipy library in Python [12] is used.

TABLE I
OPTIMAL TILT AND AZIMUTH ANGLES BY MONTH AND SEASON

Month	Maximum production		Maximum revenue		Season	Maximum production		Maximum revenue	
	Tilt (°)	Azimuth (°)	Tilt (°)	Azimuth (°)		Tilt (°)	Azimuth (°)	Tilt (°)	Azimuth (°)
January 2022	68.32	180.00	68.38	179.33	Winter	52.27	180.38	56.87	178.06
February 2022	59.19	180.00	59.61	181.82					
March 2022	45.63	180.00	46.52	187.19					
April 2022	28.14	180.00	29.86	202.93	Spring	15.40	180.55	13.40	197.61
May 2022	12.93	180.00	17.13	219.83					
June 2022	5.00	180.00	10.03	228.85					
July 2022	9.32	180.00	11.77	195.46	Summer	23.80	179.60	25.21	198.68
August 2022	22.11	179.05	24.08	177.14					
September 2022	39.61	179.74	40.06	167.45					
October 2022	55.22	180.00	55.14	165.83	Autumn	63.06	179.84	64.16	186.17
November 2022	65.57	179.37	66.09	171.90					
December 2022	70.02	179.95	69.88	172.99					
January 2023	68.35	180.30	68.35	180.25	Winter	57.35	180.38	59.39	178.68
February 2023	59.25	180.40	59.77	181.28					
March 2023	45.76	180.44	46.62	186.99					

D. Results and Discussion

Using the simulation model described in the previous sub-section, an optimization analysis was carried out to obtain the tilt and azimuth angles that result with maximum revenue and maximum production, respectively, for geographical location $41.03661°$ north latitude and $21.33492°$ east longitude. Hourly electricity prices for the period of January 2022 to March 2023 were obtained from HUPX [14]. Repeating the simulation for each month, season and for the whole year, optimal monthly, seasonally and yearly angles were calculated, and the results are presented in table 1. The values of $0°$ for the azimuth angle refers to northern, $90°$ eastern, $180°$ southern and $270°$ western orientation. The results show that the yearly optimal tilt and azimuth angles for maximizing production are $39.31°$ and $179.99°$, and those for maximizing revenue are $37.38°$ and $178.61°$ respectively. The reason for overlapping of the angles in both scenarios is the energy crisis in Europe during 2022, which resulted in low electricity prices volatility and absence of price valleys. Thus, prices remained high during mid-day resulting in maximization of PV systems revenue in period of highest production.

The values for the tilt and azimuth angles that maximize the production and revenue of the PV system for each month differ for both cases, especially the azimuth angle. Moreover, the results clearly show that the azimuth angles that maximize the revenue differ significantly from ideal south for the months that are associated with higher PV production. The analyses of the electricity prices in those days, shows more frequent occurrence of price valleys during mid-day, so to maximize the revenue, PV systems need to shift their production to periods with higher prices (morning or evening), resulting in azimuth angles that differ from ideal south. Table II presents a comparative analysis of the production and revenue obtained by orienting the PV system according to the values presented in Table I. In Table II, production and revenue for both scenarios are presented in per units of production and revenue obtained for maximum production scenario. The results show that for maximum revenue scenario, for a slightly lower production, slightly higher revenue is obtained. The highest revenue increment by changing the tilt and azimuth angles for maximum production scenario is recorded for June 2022 with 0.77% increment.

TABLE II
PRODUCTION AND REVENUE FROM PV SYSTEM FOR BOTH SCENARIOS

Month	Maximum production		Maximum revenue	
	Production	Revenue	Production	Revenue
May 2022	1.00000	1.00000	0.98673	1.00482
June 2022	1.00000	1.00000	0.99332	1.00775
July 2022	1.00000	1.00000	0.99849	1.00453

IV. CONCLUSION

In conclusion, an optimization analysis was conducted to determine the optimal tilt and azimuth angles for a PV system located at a specific geographical location, with the goal of maximizing either production or revenue. The simulation was repeated monthly, seasonally, and yearly using hourly electricity prices obtained from HUPX. The results showed that the optimal angles for maximum production and revenue were the same for the entire year due to the energy crisis in Europe. However, the optimal angles varied significantly for each month, with the azimuth angle playing a crucial role in maximizing revenue. As it is expected that in the future more price valleys during day-mid will occur, fixed-tilt PV systems will be needed to be designed differently, from orientation that yield maximum production at present to orientations that yield maximum revenue in the future.

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