Investigation and Economic Analysis of the Optimum Tilt Angle of Solar Panels for Three Cities in Azerbaijan

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Abstract*— Interest in photovoltaic solar panels, a renewable energy source, is increasing day by day, and the installation of solar panels is becoming more widespread. To achieve maximum efficiency from solar panels, they must be installed at a specific angle. In this study, a Photovoltaic Geographical Information System (PVGIS), capable of performing calculations based on latitude, longitude data, and satellite data, was used to determine the optimum tilt angle for three selected regions in Azerbaijan. The optimum tilt angles were determined for monthly, seasonal, and annual periods for the selected regions, and the global irradiation and maximum energy production values at these angles were compared. In practical applications, the tilt angle is set equal to the latitude. The energy production at the monthly, seasonal, and annual optimum tilt angles was compared with the practical application. When the tilt angle is determined annually, the gain is 0.66%, while the gain increases to 4.2% when the angle is set seasonally. When the tilt angle is adjusted monthly, the gain reaches 4.91%, achieving the highest gain. The gain increases and the efficiency of the installed panels improves when the tilt angle is determined monthly and seasonally.

Keywords*— economic analysis, global solar irradiation, photovoltaic solar panel, tilt angle.

I. INTRODUCTION

The increasing energy demand and the threat of climate change have further highlighted the significance of renewable energy sources in today's world. In this context, photovoltaic (PV) systems stand out for their ability to directly generate electricity from solar energy. With their environmentally friendly nature, near-zero carbon emissions, and capacity to provide sustainable energy production, PV systems play a critical role in the transition to renewable energy [1, 2]. Particularly in recent years, the significant reduction in PV technology costs has made these systems more economically accessible. The decreasing installation costs of solar energy systems have lowered energy production expenses, offering long-term economic savings for energy consumers. Additionally, they provide economic benefits such as the creation of local employment and the reduction of dependence on foreign energy supply. These systems can be implemented at various scales, ranging from rooftops to large solar farms. Therefore, PV systems are not only a key element in the environmental transformation of the energy sector but also play a crucial role in its economic transformation.

According to the renewable energy statistics published by the International Renewable Energy Agency (IRENA) [3] in July 2024, the energy capacity and energy production data provided by Solar PV in the world and Azerbaijan are presented in Table 1. Solar PV capacity and energy produced are increasing day by day in the world and in Azerbaijan.

TABLE I. THE AMOUNT OF ENERGY OBTAINED FROM RENEWABLE ENERGY SOURCES AND INCREASE RATES IN 2023.

		2020	***2021***	***2022***	***2023***
World	Production (GWh)	822 515	1 016 898	1 281 654	-
	Capacity (MW)	719 813	864 266	1 064 275	1 411 139
Azerbaijan	Production (GWh)	47	55	61	-
	Capacity (MW)	35	48	51	282

Photovoltaic technology is the equipment used to produce electrical energy from solar energy. Photovoltaic panels convert solar radiation reaching the surface into electrical energy through the via of cells inside them. Panel tilt angle is a critical factor in maximizing electrical energy production in photovoltaic (PV) systems. The amount of solar radiation incident on the surface of solar panels varies depending on the geographic latitude of the panel's location, the time of year, and the time of day. Therefore, positioning the panels at the optimal tilt angle ensures maximum efficiency in harnessing solar energy. For instance, in fixed-tilt systems, the panels are typically installed with an inclination equal to

the latitude of the region, while adjustable systems, which account for the changing solar angle throughout the year, offer a higher energy production potential. Moreover, properly adjusting the tilt angle reduces factors such as dirt accumulation and water pooling, thereby enhancing the long-term performance of the panels. Therefore, accurately determining the tilt angle of the panels in PV systems not only increases energy efficiency but also shortens the payback period of the system from an economic perspective.

One of the most important factors affecting the performance of PV systems is the optimization of the panel tilt angle. Studies in the literature indicate that the optimal tilt angle varies depending on geographic latitude, seasonal sunshine duration, and local weather conditions. For example, a study conducted by Duffie et al. [4] found that the optimal tilt angle for fixed-tilt PV systems is generally approximately equal to the latitude of the region where the panels are installed. Similarly, in the study conducted by Abdelaal et al. [5], the optimum tilt angle was determined for some cities in Egypt on a daily, monthly, seasonal and annual basis. It was found that changing the tilt angle twice a year provided the best solar radiation.

On the other hand, some studies in the literature have highlighted the performance advantages of dynamic and adjustable PV systems. Arslan et al. [6] compared the current and power factors of PV panels for different azimuth and tilt angles. They stated that tilt and azimuth angles affect the PV system efficiency. Additionally, Sen and Sahin [7], in a study conducted in Turkey, analyzed the recommended optimal tilt angles for different geographical regions and found that using a steeper angle in winter and a flatter angle in summer significantly increases the energy production potential. These studies demonstrate that the tilt angle of PV panels can not only enhance energy production but also improve economic performance.

According to the performance analysis conducted by Chandel and Chandel [8] at a 19 MWp solar power plant in India, fixed-tilt systems produced 6% less annual energy compared to seasonally adjustable tilt systems, and 15.4% less compared to horizontal single-axis solar trackers. However, the installation cost of fixed-tilt systems was 8% lower compared to seasonally adjustable systems and 176.1% lower compared to horizontal tracking systems. The study highlighted the differences between energy production and costs.

Masour et al. [9] conducted a study to determine the monthly and annual optimum tilt angle for five cities in the Kingdom of Saudi Arabia. In their study, they found that the annual optimum tilt angle was close to the latitude of the cities. They also showed with their results that the ambient temperature, as well as the panel tilt, also affects the PV system performance.

Lu and Qin [10] aimed to determine the optimal tilt angle that would achieve maximum efficiency for solar power systems to be installed in China. In their study, they identified the tilt angle for the highest solar radiation value during different periods. They emphasized that this would lead to a significant increase in annual energy production.

Zaheb et al. [11] studied the system efficiency according to seasonal tilt angle and different sun tracking scenarios. It was observed that there was a significant increase in electricity production with the applied single-axis sun tracking system. The economic analysis was compared with the installation and maintenance costs.

As seen in the literature review, there are regional studies on the tilt angle affecting the performance of PV panels. However, studies specifically focused on Azerbaijan are insufficient. Therefore, in this study, the optimal tilt angle for maximizing the efficiency of PV systems in the regions of Baku, Nakhchivan, and Shusha is calculated using the PVGIS module, with the aim of contributing to the literature. This study provides a guiding influence for the systems planned to be installed in the selected cities of Azerbaijan. Additionally, an economic analysis was conducted as part of the optimal tilt angle planning and presented to industry leaders. Through this study, the impact on both global and local economies, along with maximum panel efficiency and economic gains, has been demonstrated.

II. Material Method

In this study, the optimum tilt angle for the cities of Baku, Nakhchivan, and Shusha was determined for monthly, seasonal, and annual periods using the Photovoltaic Geographical Information System (PVGIS) module. The PVGIS module is an online simulation tool financed and developed by the European Commission. This program, through satellite interaction, calculates the system performance by considering meteorological data, panel type, system losses, and grid connection status in on/off modes [12]. In the PVGIS module, the total power P (W) is calculated using Equations (1-4).

$$P(G',T') = G'(P_{STC,m} + k_1 ln(G') + k_2 ln(G')^2 + k_3 T' + k_4 T' ln(G') + k_4 T' ln(G')^2 + k_6 G'^2) \quad (1)$$

$$G'_T \equiv G/G_{STC} \quad (2)$$

$$T' \equiv T_{mod} - T_{STC} \quad (3)$$

$$\eta_{rel}(G'_T, T') \equiv P(G'_T, T')/P_{STC}, mG'_T \quad (4)$$

In the equations used in the database, T represents the panel temperature in Celsius, $k_{1\text{-}6}$ are constants measured according to the panel type by the European Solar Test Installation (ESTI), G_T' is the normalized total solar radiation, and P_{STC} represents the maximum power under standard test conditions. Under standard test conditions, $T_{STC} = 25°C$ and $G_{STC} = 1000\ W/m^2$ are taken, and the T_{mod} term represents the PV module temperature, while η_{rel} denotes the panel efficiency.

In this study, three different cities have been selected in Azerbaijan to determine the optimal tilt angle for maximizing electricity production from photovoltaic panel systems. The selected cities are the capital Baku, Nakhchivan, and Shusha. The latitude and longitude information for these cities is presented in Table II.

TABLE II. The Coordinates of the Selected Cities.

City	Latitude	Longitude
Baku	40.367	49.831
Nakhchivan	39.207	45.408
Shusha	39.754	46.746

Using satellite data for different coordinates, solar radiation and maximum energy production data corresponding to different angle values can be obtained with the help of the PVGIS module. In this study, optimal angle values were determined on a monthly, seasonal, and annual basis in the PVGIS module, and the results were compared.

- The monthly optimum tilt angle was determined by incrementally changing the tilt angle between 0° and 90° in the PVGIS, with the angle corresponding to maximum energy production (E_{max} - kWh) and maximum solar radiation (H - kWh/m²).
- For the seasonal optimal tilt angle, total energy production and total solar radiation were calculated for the months constituting each season, and the angle(s) corresponding to the maximum values were determined.
- For the annual optimal tilt angle, the total E and H values for the twelve months were calculated, and the angle corresponding to the maximum value was determined.

III. Results and Discussions

In this section, the results obtained are presented on a monthly, seasonal, and annually for each city. The monthly optimal tilt angles and the corresponding maximum energy production and global radiation values are presented in Table III. When the monthly optimum tilt angles were determined for the three selected cities, the lowest tilt angle of 5° was observed in June, while the highest tilt angle of 63-64° was observed in December in Shusha. For Baku, the highest optimum tilt angle was 62-63°, and for Nakhchivan, it was 63-64°. The lowest optimum tilt angle is 9° for Baku and 7-8° for Nakhchivan. The highest energy production (E_{max}) of 165.5 kWh occurs in Nakhchivan in July, with a global irradiation of 232 kWh/m². Fig. 1 presents a graph showing the monthly variation in average electricity production for the three selected cities, while Fig. 2 displays a graph illustrating the variation in average total global irradiation per square meter.

After determining the monthly optimum tilt angles, the seasonal optimum tilt angles were identified, and the seasonal optimum tilt angle, along with the corresponding maximum energy production and global irradiation results, are presented in Table IV.

When the seasonal analysis results are examined, it is observed that the lowest optimum tilt angle is 8° in summer and the highest tilt angle is 62° in winter. While the lowest optimum tilt angle for Baku is observed as 15-16° in summer, this angle value increases to 57-58° in winter depending on the angle of incidence of solar irradiation. The lowest energy production is in winter with 209.22 kWh, while the highest energy production is in summer with 465.39 kWh. For Nakhchivan, the lowest optimum tilt angle value is observed with 10° in summer with 471.10 kWh

TABLE III. The monthly optimum tilt angles for Baku, Nakhchivan, and Shusha.

Months	Parameter	Baku	Nakhchivan	Shusha
January	***Tilt Angle (°)***	60	58-62	61-62
	Emax (kWh)	70.29	85.10	89.88
	H (kWh/m²)	82.06	101	105.77
February	***Tilt Angle***	50-51	52	51-52
	Emax (kWh)	72.71	94.8	86.36
	H (kWh/m²)	84.76	115.7	102.99
March	***Tilt Angle***	39-40	40-42	38
	Emax (kWh)	105.51	123.4	97.45
	H (kWh/m²)	126.19	156.3	120.09
April	***Tilt Angle***	27	25-28	22-23
	Emax (kWh)	123.25	128	102.27
	H (kWh/m²)	152.07	167.5	128.70
May	***Tilt Angle***	16	13-14	10-11
	Emax (kWh)	152.05	145.7	113.96
	H (kWh/m²)	193.97	194.8	146.54
June	***Tilt Angle***	9	7-8	5
	Emax (kWh)	160.46	160.5	128.85
	H (kWh/m²)	209.59	222.7	168.62
July	***Tilt Angle***	14	12	8-10
	Emax (kWh)	157.69	165.5	130.30
	H (kWh/m²)	207.02	232	171.10
August	***Tilt Angle***	24	23	21
	Emax (kWh)	148.87	160.60	128.51
	H (kWh/m²)	195.06	221	168.86
September	***Tilt Angle***	37	36-39	33-34
	Emax (kWh)	124.98	147.8	100.54
	H (kWh/m²)	159.81	198.40	129.83
October	***Tilt Angle***	48-49	49-52	48
	Emax (kWh)	90.83	124.7	94.43
	H (kWh/m²)	120.59	161.10	118.80
November	***Tilt Angle***	58	60-61	59-60
	Emax (kWh)	71.77	111.8	89.78
	H (kWh/m²)	86.28	137.1	108.61
December	***Tilt Angle***	62-63	63-64	64-65
	Emax (kWh)	66.88	84.5	91.70
	H (kWh/m²)	78.83	101.8	108.64

energy production and 648.90 kWh/m^2 global irradiation value, while the highest optimum tilt angle value is observed with 62° with 281.40 kWh energy production and 339.70 kWh/m^2 global irradiation value. Seasonal E_{max} values of the selected cities are presented comparatively in Figure 3, and H values are presented in Figure 4.

When Fig.3 and Fig.4 are examined, it is observed that Shusha has the lowest energy production and global irradiation values except in winter. Due to its location, Nakhchivan, which is located in the south, has the highest global irradiation and average energy production values except in spring. When the results for Baku are examined, it is seen that it has higher energy production than other cities in spring.

After determining the monthly and seasonal optimum tilt angle for the selected cities, the annual optimum tilt angle value was determined and the results are presented in Table V. The annual optimum tilt angle for the selected cities varies between 32° and 35°. The lowest annual global irradiation value per square meter was observed in Shusha with 1508.61 kWh/m^2. Accordingly, the lowest annual energy production was observed in Shusha with 1197.15 kWh, while the highest energy production was observed in Nakhchivan with 1467.40 kWh.

Annual total energy production data and global irradiation values per m^2 are given comparatively in Figure 5 and Figure 6. Nakhchivan's annual energy production amount is 22.5% more than Shusha and 12.5% more than Baku. In addition, global irradiation value is 27.6% more than Shusha and 17.36% more than Baku in Nakhchivan. When the results are compared, it is seen that it is appropriate to install a PV system in Nakhchivan, which has the highest global irradiation value and therefore the highest energy production capacity.

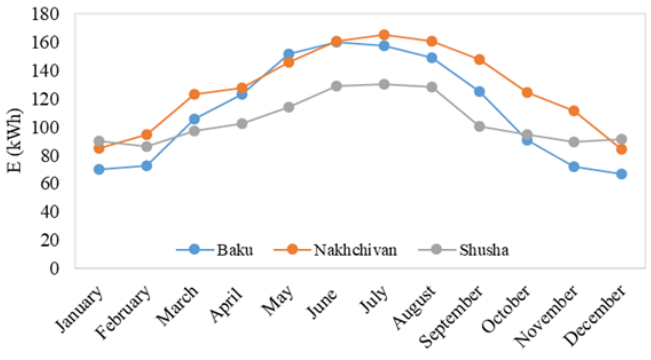


Fig 1. Monthly average energy production of three cities.

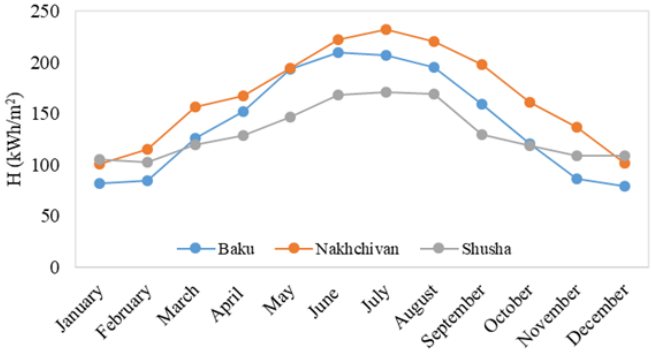


Fig 2. Monthly sum of global irratiation per square meter of three cities.

The tilt angle of PV panels is typically set equal to the latitude of the region where they are installed in practical applications. Therefore, the monthly, annual, and seasonal variations in solar irradiance and the potential energy gain from these variations are often neglected. As a result, it is crucial to calculate the energy gain that can be achieved from the change in the optimal tilt angle. In this study, an economic analysis was conducted to determine the energy gain obtained by placing PV panels at the determined optimal tilt angle, compared to practical applications. Table VI presents the energy produced and the gain relative to

TABLE IV. THE SEASONALLY OPTIMUM TILT ANGLES FOR BAKU, NAKHCHIVAN, AND SHUSHA.

Seasons	Parameters	Baku	Nakhchivan	Shusha
Winter	Tilt Angle	57-58	62	62
	Emax (kWh)	209.22	281.40	271.22
	H (kWh/m^2)	244.89	339.70	322.84
Spring	Tilt Angle	25-27	38-40	37-38
	Emax (kWh)	377.13	342.2	282.15
	H (kWh/m^2)	467.96	434.10	346.97
Summer	Tilt Angle	15-16	10	8
	Emax (kWh)	465.39	471.40	373
	H (kWh/m^2)	609.61	648.90	486.11
Autumn	Tilt Angle	46	35-36	33
	Emax (kWh)	291.07	426.70	319.04
	H (kWh/m^2)	363.65	572.10	411.85

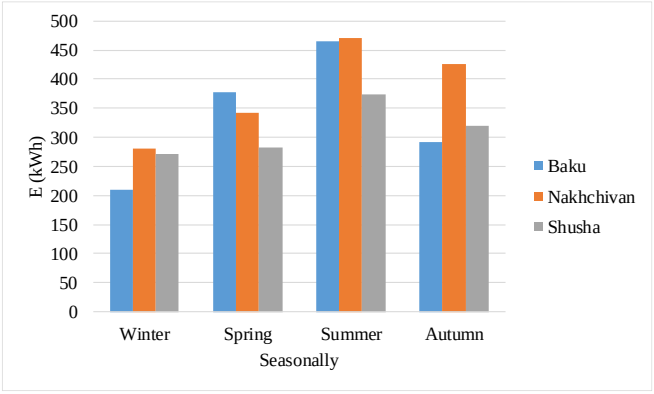


Fig 3. Seasonally average energy production of three cities.

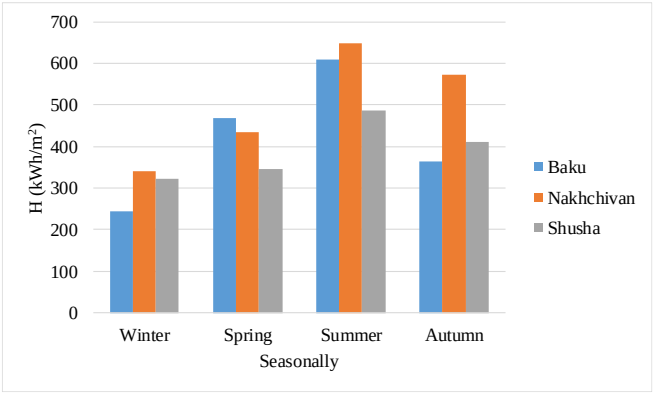


Fig. 4. Seasonally sum of global irradiation per square meter of three cities.

TABLE V. ANNUALLY OPTIMUM TILT ANGLE OF BAKU, NAKHCHIVAN AND SHUSHA

Yearly	Parameters	Baku	Nakhchivan	Shusha
Annually	Tilt Angle	32	35	35
	Emax (kWh)	1304.05	1467.40	1197.15
	H (kWh/m^2)	1640.55	1925.40	1508.61

practical applications for the variations in the optimal tilt angle on a monthly, seasonal, and annual basis.

According to the domestic electricity prices announced by the Azerbaijan Energy Regulatory Agency (AERA), the unit cost of electricity is determined as 0.039$/kWh. [13]. The total energy cost for the selected regions was calculated for different periods based on the optimum tilt angles and the latitude angle used in practical applications, and the results are presented in Table VI.

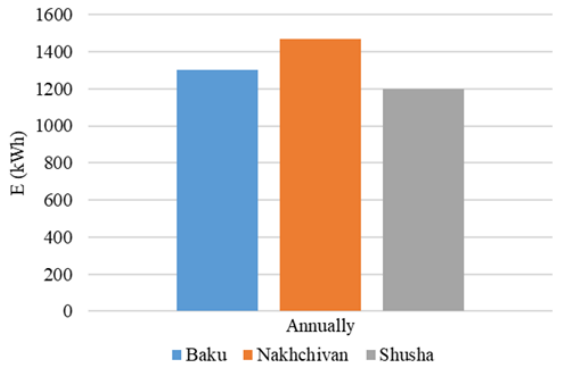


Fig 5. Aaverage energy production of three cities.

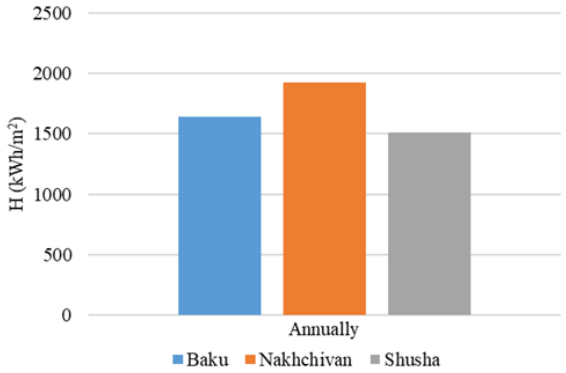


Fig. 6. Annually sum of global irratiation per square meter of three cities.

TABLE VI. COMPARISON OF MAXIMUM ENERGY PRODUCTION WITH DIFFERENT PERIODS

Total Energy Production	**Baku**	**Nakhchivan**	**Shusha**
Monthly Tilt Angle (kWh)	1345.29 (3.85%)	1532.4 (4.69%)	1254.03 (4.92%)
Gain with monthly tilt angle ($/kWh)	52.46	59.76	48.90
Seasonally Tilt Angle (kWh)	1342.81 (3.65%)	1521.7 (3.96%)	1245.41 (4.2%)
Gain with seasonally tilt angle ($/kWh)	52.36	59.34	48.57
Annually Tilt angle (kWh)	1304.05 (0.66%)	1467.4 (0.25%)	1197.15 (0.16%)
Gain with annually tilt angle ($/kWh)	50.86	57.23	46.69
Latitude Angle (kWh)	1295.4	1463.69	1195.18
Gain with latitude angle ($/kWh)	50.52	57.08	46.61

The highest difference in energy production, 0.66%, was observed in Baku when the tilt angle of the PV panels was set equal to the latitude of the region, compared to the case where the tilt angle was calculated annually. The lowest difference, 0.25%, was observed in Nakhchivan.

It has been observed that the difference in energy production increased when the tilt angle was calculated seasonally using the PVGIS module. The lowest difference, 3.65%, was observed in Baku, while the highest difference, 4.2%, was observed in Shusha. When the tilt angle was calculated on a monthly basis, the difference in energy production increased significantly across all regions. Compared to the case where the tilt angle was set according to the latitude, gains of 3.85%, 4.69%, and 4.92% are observed in Baku, Nakhchivan, and Shusha, respectively.

Yunus Han et al. [14] in their study, showed that determining the optimum tilt angle for the PV system on a monthly basis provides the highest performance compared to seasonal and annual determinations, but it is costly. They also showed that the solar tracking system provides higher energy production compared to manual and fixed tilt angles. In their study, Tuama et al. [15] examined the effects of various tilt angles and orientations on productivity in PV systems. They observed that small tilt angles in summer and large tilt angles in winter increased, and they concluded that performance improved with the two-season configuration.

IV. CONCLUSIONS

In the present study, the PV panel tilt angles for three selected regions in Azerbaijan were determined using the PVGIS module. Analyses were conducted for the variation of the tilt angle over different periods, and the optimum tilt angles for monthly, seasonal, and annual periods, along with the corresponding maximum energy production, were compared. The obtained results can be summarized as follows:

- In the PVGIS module, the optimum tilt angles for the selected regions were determined based on the average global irradiation values for monthly, seasonal, and annual periods, and the corresponding maximum energy production.
- By determining the tilt angle annually, a 0.66% gain in maximum energy production was achieved compared to the case where the latitude angle was used as the tilt angle.
- When the optimum tilt angle was determined seasonally, a 4.2% gain was achieved compared to the case where the latitude angle was used as the tilt angle.
- For the selected regions, when the optimum tilt angle was determined monthly, the gain reached its maximum value at 4.91%.
- The highest gain values were obtained when the tilt angle was adjusted monthly.

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