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EXPERIMENTAL STUDY TO GAUGE THE INFLUENCE OF TILT ANGLE ON PHOTOVOLTAIC PANEL PERFORMANCE

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Solar energy is the most significant form of renewable energy, and its efficiency is affected by the angle between the photovoltaic module and the sun. Research has been conducted to enhance its sustainability, cost-effectiveness, and efficiency. The power density of a PV module is highest when it is perpendicular to the sun's beam. Still, because the sun's angle with a fixed panel constantly changes, the power density on a fixed PV module is lower than that of the incident sunlight. Additionally, the earth's orbit and the changing seasons impact irradiance and reduce the output of fixed tilt angle panels. This study aims to estimate the power losses due to fixed PV panels using an analytical model and experimental data and compare the calculated output with data from solar panel installations. The results of this research can help overcome the drawbacks of fixed tilt angles, improve efficiency, increase solar energy production, and reduce dependence on environmentally harmful non-renewable energy sources.

1. INTRODUCTION

In the modern world, there is a need to pay attention to renewable energy resources (RES) because of the shortage of nonrenewable counterparts. RESs strengthen energy independence by lowering dependence on fossil fuels. Renewable energy costs have declined significantly in recent years, making them increasingly competitive with traditional fossil fuel-based energy sources [1,2]. Non-conventional energy sources (sunlight, wind, biogas, tidal, etc.) play an essential role in distributed generation that provides ease to long-distance consumers of electricity [3]. Photovoltaic (PV) systems are becoming increasingly popular due to the declining cost of solar panels and the growing demand for clean and green energy. The commercialization and cost reduction of the PV panel paved the way for green and clean energy to be adopted by different underdeveloped countries [4]. Storage systems are also installed to store the electricity and supply uninterrupted power to consumers [5]. Various types of algorithms have been used to detect faults among the PV panels and predict the life span of PV panels in different conditions to maintain the reliability of the PV system [6].

PV panels consist of photovoltaic cells made of silicon or other materials that absorb sunlight and convert it into electricity [7,8]. Despite using higher efficiency solar cells, incorrect tilt angles of PV panels result in low output power. The PV module must be perpendicular to the sunlight to receive maximum irradiance. The solution to receive maximum sunlight is to install a tracking system that continuously follows the sun’s path. Still, this tracking mechanism increases the cost, which is not suitable from a commercial point of view. Fixed PV panels have fixed tilt angles throughout the year [9,10]. Due to the Earth’s rotation in its orbit and around the sun, the Earth’s surface receives solar radiation at different rates throughout the year. Therefore, PV modules are placed with optimized tilt angles with different values for every season. Solar irradiance varies with distinct seasons as the Earth continuously spins around the sun. Suppose the tilt angle is fixed throughout the year according to one season. In that case, this will lead to a decrease in irradiance falling on the panel’s surface in other seasons, causing a reduction in the output power and efficiency [11,12]. Temperature plays a vital role in the PV panel’s output. The short circuit current of PV cells slightly increases with an increase in temperature; when the temperature rises, it reduces the band gap of the semiconductor, which increases the short circuit current. This increase in temperature also affects voltage, which is reduced, and efficiency decreases [13].

The PV panel’s output also depends on the tilt angle. The output power will be maximum when solar irradiance is perpendicular to the solar panel surface [14]. Earth spins 360 ° from east to west per day. Earth is continuously evolving, and the angle between solar irradiance and the PV panel's surface changes, which decreases the efficiency of PV panels. Solar radiation is directly proportional to the PV output, so as the solar radiation increases, the PV module’s output also increases [15]. Standalone and remote PV panels mostly have fixed tilt angles throughout the year. As solar irradiance varies with different seasons, a fixed tilt angle will decrease the irradiance falling on the panel's surface in other seasons, causing voltage and current to reduce, ultimately diminishing the power and efficiency [16].

In the past two decades, several researchers have conducted studies regarding tilt angles and their effects on the performance of PV modules. Different solar PV modules' output and deterioration characteristics have been studied from various angles and directions; sufficient data were collected from other testing facilities and reported [17]. The monocrystalline PV module's output performance in Egypt's hot environment was theoretically examined from different tilt angles and directions. It was further simulated using TRNSYS software to validate theoretical results. The optimal angle was suggested between 20° to 30°; along with that, under the limitations of these tilt angles, the horizontal panels achieved an output of up to 95%, and vertical panels east-facing achieved 41% during the whole year, reported in [18].

A mathematical model was developed to gauge the performance of solar PV modules installed in Sanliurfa, Turkey, on a horizontal plane. The study shows that the minimum change in the tilt angle of 13° was observed in June, and a maximum change of 61° in December. Tilt angle has a significant effect on the performance output of the PV modules [19]. In 2009, the performance of the PV module output was

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analyzed using different directions and tilt angles in Taiwan by applying a single tracking system. The output of the fixed solar panel module was measured to be 10.2% [20]. A helpful tool was proposed to set the modules to produce maximum production, yielding different tilt angles with specific design considerations [21]. An algorithm related to sun tracking was proposed. The algorithm is based on a mathematical model that calculates the best direction of the sun to gain maximum irradiance using the Julian dating procedure. The result depicts a minimum difference in actual and simulated angles [22].

In 2011, research was conducted on the effect of tilt angle on large-scale PV module plants of a capacity of 100 kW on different inclination angles. Each array consisting of 10 kW was arranged at 10°, 20°, and 30°, and the initial results show sufficient evidence of the inclination effect in polycrystalline and thin film solar PV module arrays [23]. An experimental study was conducted in Madinah, KSA, in 2011 to gauge the impact of tilt angle on the power output of the solar PV module, and an 8% increase in power output was reported compared to fixed angle [24]. A model was proposed to verify the irradiance given in the NREL database. The model validated all the data available regarding tilt angle and presented in [25]. An optimal tilt angle between 7° and 12° was observed in icy weather conditions in Ontario, Canada, and was reported [26]. Experiments were carried out in eight different provinces of Turkey in 2012. The optimum tilt angle was varied from 0° to 90°, where angles were increased with 1° step size to notice maximum output. The minimum optimum tilt angle reaches 0° in June–July. The optimal tilt angle increased throughout winter and peaked in December across all provinces. [27]. PV system performance was examined in Brisbane, Australia, in 2013. Theoretical and experimental readings were matched; one year-long data from the University of Queensland was compared with theoretical estimation, and a slight deviation was found. It was also calculated that the optimum tilt angle for Australia is 26º towards the North [28].

In Surabaya (Indonesia), the optimum tilt angle was calculated using mathematical equations, where the main parameters were surface orientation, day, time, and latitude. The optimum tilt angle in summer varied between 0º–40º and in winter 0º–30º. This research work also suggested two collectors be installed, one facing the East (morning) and the other facing the West (afternoon). The annual optimum tilt angle was between 36º – and 39.4 º [29]. In 2015, an interesting research work on hybrid system (PV/DG/battery) optimal sizing was published, which also included optimum tilting of PV modules for different remote areas of India without using any metrological data. It was observed that the irradiation values increased by 23.56% and 29.64% during the third and fourth seasons, respectively. [30]. In Cyprus, experimental research was conducted at five places at Cyprus International University. Dust, orientation, and tilt angle were the primary considerations. The researchers compared one year of measured data, analytical calculations, and simulated data. It was presented that the tilt angle must be lower than the latitude in summer and higher in winter. After the cleaning process, performance was increased; it was also found that mathematical models are better than simulated data [31].

An experiment involving a variation of tilt angle from 0º to 80º was performed under constant and variable irradiance in 2018, and the finite element method (FEM) was used to numerically analyze the tilt angle for different irradiance levels, with a step size of 100 W/m^2. Both experimental and numerical approaches noticed increased power output and temperature. For every 5º rise in the tilt angle of the module, a decrease in the output performance was noticed through both approaches [32]. In 2019, a series of experiments were carried out in various cities in Pakistan to validate the simulated data. The optimum tilt angle for PV panels was estimated using MATLAB, optimization code, and NREL irradiance data for the last 17 years. The results showed a slight difference between simulated and experimental readings; a 6.6% increase in output was observed on four different tilt angles [33]. To obtain overall equations for optimum tilt angle on a daily, monthly, and yearly basis worldwide, a model was introduced in 2020, which examined 337 locations in the northern hemisphere and 247 in the southern hemisphere. It was concluded that the optimum tilt angle is independent of longitude but depends on latitude. The results were compared with other research works and agreed with them [34].

$$Ho = \frac{24}{\pi} I_{SC} \left(1 + 0.33 \cos\left(\frac{360n}{365}\right)\right)(\cos\phi \cos\delta \sin\omega + + \frac{2\pi\omega}{360} \sin\phi \sin\omega). \tag{1}$$

This study aims to investigate the impact of a fixed tilt angle on power loss through a comparative analysis of analytical calculations and experimental data. The parameters to be computed for determining the power output loss include short circuit current, open circuit voltage, irradiance, maximum power, and tilt angle. The paper is structured into four distinct sections, with section 1 encompassing the introduction and a comprehensive review of relevant literature. Section 2 provides an overview of the methodology employed in this research. The investigation outcomes are discussed in section 3, while section 4 summarizes the conclusions.

2. METHODOLOGY

In this section, the methodology of the proposed research work is presented. The literature review has revealed that an incorrect tilt angle decreases the output power and efficiency of the PV module. This research focuses on calculating power losses due to incorrect tilt angles. Proposed research is being done using analytical and experimental approaches, and the results will be compared in the next section. Polycrystalline PV panels have been used with the specifications mentioned in Table 1. The output power has been calculated from 9:00 am to 4:00 pm for an hourly interval for three different days in February and March 2022.

Table 1

PV Panel Description (HG-50W)

Specifications	*Parameters*
Output Peak Power	50 W
Open circuit voltage	21.4 V
Short circuit current	3.01 A
Max power voltage	18.1 V
Max power current	2.76 A
Number of Cells	36
Maximum System Voltage	1000 VDC

Figure 1 depicts the comprehensive process involved in determining the output power of a PV panel, which includes the input of solar panel irradiance. Calculating the output power and efficiency is initiated by computing the open-circuit voltage and short-circuit current. The analysis of output power and efficiency is carried out through analytical and experimental methods, allowing for observing variation in output power, highlighting the loss caused by a fixed tilt angle.

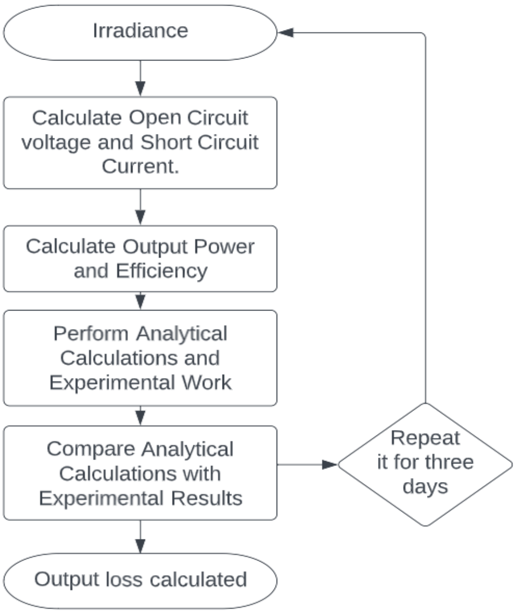

Fig. 1 – Power loss analysis flow diagram due to incorrect inclination.

3. ANALYTICAL APPROACH

To assess the power loss resulting from incorrect tilt angle, the irradiance is considered the primary factor responsible for generating power from PV panels. The daily irradiance level can be determined analytically or by utilizing a lux meter, which provides the irradiance data for a particular day. The Hay, Davies, Klucher, and Reindl (HDKR) model is used to calculate irradiance in this research work. The solar panel's output power mainly relies on the open circuit voltage and short circuit current, which must be calculated first. Upon determining all the unknown parameters, the output voltage can be obtained, and subsequently, the results are compared to estimate the power loss.

The analytical model used in this research study is focused on tilt angle impact by excluding external factors like dust and shade on the PV panel. Analytical calculations were performed by calculating the output of the PV panel in terms of current, voltage, power, and efficiency at STC (standard test conditions) and NOCT (nominal operating cell temperature) [35]. These equations are simultaneously transformed with Ohm's law equations to determine the PV panel's output. Determining irradiance is the first step in the analytical method for PV panel output losses. Details such as the number of days, latitude, longitude, azimuth angle, albedo% %, and clearness index of the site, time, zone, and altitude must be known to compute irradiance for a particular place, time, and day of the year. Hay, Davies, Klucher, and Reindl's model (HDKR model) has been used to calculate irradiance falls on the surface of PV panels under [36]:

$$\bar{G}_T = (\bar{G}_b + \bar{G}_d\ A_i)\,R_b + \bar{G}_d\ (1 - A_i)\left[\frac{1+\cos\beta}{2}\right]\left[1 + f\sin\left(3\frac{\beta}{2}\right)\right] + \bar{G}_{pg}\left[\frac{1-\cos\beta}{2}\right], \quad (2)$$

where $\bar{G}$ is the averaged global horizontal radiation on the earth's surface [W/m^2], $\bar{G}_b$ is the beam irradiance [W/m^2]. $\bar{G}_d$ is the diffuse irradiance [W/m^2], A_i is the anisotropy index, R_b is the ratio of the beam striking on a horizontal plane to the beam striking on an inclined surface, f is the cloudiness, B is the slope of the surface [degree], and pg is the albedo [%].To calculate short circuit current (I_{SC}) and open circuit voltage (V_{OC}) concerning irradiance (G) and ambient temperature (T) is [37–39]:

$$I_{SC}(G, T) = I_{SC} \times \frac{G}{G_{STC}}\,[1 + \delta I_{SC}(T - T_{SC})], \quad (3)$$

$$V_{OC}(G,T) = V_{OC}\left[1 + \delta V_{OC}{}^{G}\left(\ln(G) - \ln(G_{STC})\right)\right]\times$$
$$\times\left[1 + \delta V_{OC}{}^{T}(T - T_{STC})\right], \quad (4)$$

where G is global irradiance, G_{STC} is irradiance at STC, δI_{SC} is the temperature coefficient at I_{SC}, $\delta V_{OC}{}^{T}$ is the temperature coefficient at $V_{OC,}$ and $\delta V_{OC}{}^{G}$ is the irradiance correction coefficient. The output power is calculated by using a general equation 4 of the PV module's power:

$$P_{max} = \text{FF} \times (G,T) \times (G,T), \quad (5)$$

where FF is the fill factor of the PV module and is calculated using the following relation represented by

$$\text{FF} = \frac{V_{MP}\,I_{MP}}{V_{OC}\,I_{SC}}. \quad (6)$$

4. EXPERIMENTAL APPROACH

Experimental work was conducted on the ground surface in Karachi, Pakistan, with a longitude of 67.00° and a latitude of 24.86°. Two PV panels with the same configuration were used to calculate the effect of tilt angle on the output power. Comparisons were made in winter, and three different days were selected. On 14th February 2022, PV panels were installed at a winter angle of 40^o and a summer angle of 10^o in the winter season. On 18th February 2022, PV panels were installed at a winter angle 40^o and mid-angle at 25^o in winter. On 16th March 2022, PV panels were installed at a mid-angle of 25^o and a summer angle of 10^o in winter. Irradiance, voltage, and current were measured on every day above. The experiments were performed over three different days, during which two PV panels with the specifications mentioned in Table 1 were placed at two different angles simultaneously, from 9:00 to 14:00, without any external factors such as clouds or other disturbances affecting the performance of the PV panels.

Fig. 2 – Solar panels at different tilt angles on the site.

The experiments aimed to compare the output power generated by the PV panels at different tilt angles. The experiment was carried out uninterruptedly throughout the day, with solar irradiance being one of the key factors. It was measured by a calibrated lux meter, and its irradiance calculation ranged between 0 and 1,500 W/m^2. The temperature was recorded using a K-type thermocouple on the body of the PV panels. Voltage and current are the most critical parameters for output power, and they were measured with high accuracy. To compare and better understand the impact of tilt angle, Figure 2 depicts a location where PV panels were mounted at two different angles. These two PV panels were observed concurrently, and each PV panel's hourly output power was computed.

5. RESULTS

The effect of tilt angle on the PV panel is discussed in this section. Figures 3 and 4 show the graphs of output power calculated analytically and experimentally for three days by placing PV panels at various angles. This can be seen during the early hours when low output power was recorded; meanwhile, at noon, the graph shows a peak at maximum value as the sun was directly above the PV panels. In the afternoon, graphs show a decline in the output power as the sun moves from its perpendicular position to the PV panel's surface. In the analytical model, the external factors, including dust and shade, are not considered to focus on the angle impact on the output of the PV panels.

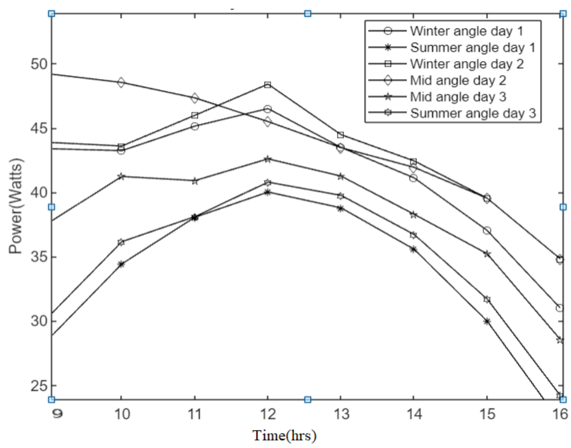

Fig. 3 – Analytically calculated output power.

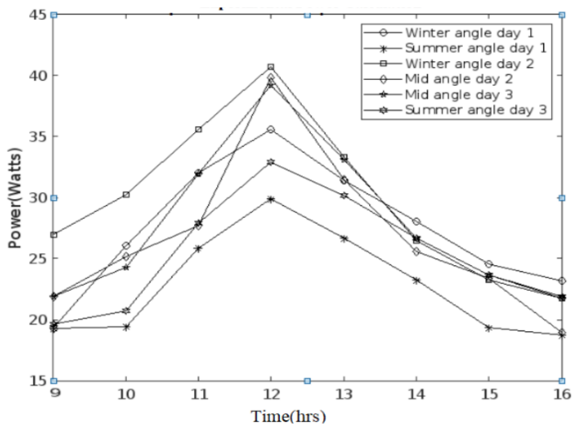

Fig. 4 – Experimentally measured output power.

Tables 2 and 3 summarize all measurements and show that the peak value was observed when PV panels were perpendicular to the sunlight at noontime. Experimental and analytical results indicate that PV panels positioned at a winter angle demonstrate increased output power compared to other orientations.

Table 2

Output power (analytical)

Time	*Output Power at Different Days Winter: w Summer: s Mid: m Angle: ° 1:2:3: Represents day*					
	W° 1	**S° 1**	**W° 2**	**M° 2**	**M° 3**	**S° 3**
9:00	43.39	28.61	42.89	49.21	37.64	30.35
10:00	43.44	34.43	43.60	48.54	41.23	36.16
11:00	45.15	38.06	45.99	47.34	41.91	38.11
12:00	46.15	40.62	48.41	45.50	42.60	40.79
01:00	43.49	38.79	44.48	43.47	41.26	39.76
02:00	41.12	35.57	42.44	36.94	38.92	36.72
03:00	37.03	29.98	39.54	32.54	35.22	31.70
04:00	31.0	22.14	34.83	30.83	28.56	24.20
Aver	41.35	33.53	42.77	41.8	38.42	34.72

Table 3

Output power (analytical)

Time	*Output Power at Different Days Winter: w Summer: s Mid: m Angle: ° 1:2:3: Represents day*					
	W° 1	**S° 1**	**W° 2**	**M° 2**	**M° 3**	**S° 3**
9:00	19.30	19.27	26.93	21.90	21.9	19.65
10:00	26.04	19.41	30.24	25.16	24.28	19.22
11:00	32.01	25.83	35.55	27.71	31.05	27.9
12:00	35.56	25.41	40.73	39.86	39.19	32.91
01:00	31.43	26.67	33.3	31.5	33.15	30.15
02:00	26.60	23.22	26.5	24.12	26.67	26.7
03:00	24.54	19.58	23.24	23.38	23.69	23.69
04:00	23.21	18.70	21.75	18.46	21.75	21.90
Aver	27.34	22.26	29.78	26.51	27.71	25.27

Measurements were taken on three different days. On Day 1, PV panels were placed at the winter and summer angles on 14th February 2022, in the winter season. On Day 2, PV panels were placed at the winter and mid angles on 18th February 2022, in the winter season. On Day 3, PV panels were placed at the mid-angle and summer angle on 16th March 2022. In Fig. 3, the plots of the analytical output power for all the days are shown, where it is observed that PV panels (placed at winter angle) in the winter season have more output power than PV panels placed at summer angle and mid-angle. Similarly, Figure 4 shows the experimental results for output power calculated on the site. It is observed that PV panels were placed at a winter angle, which is +15 degrees of latitude; results show that PV panels (placed at a winter angle) have more output power than other PV panels at different angles. The maximum peak is observed at noon. Accurate values of all calculations and measurements are given in Tables 2 and 3.

Table 4 shows the difference between analytical calculations and experimental measurements. On day 1, it was found that the power difference between the winter angle and summer angle, analytically, is 19% and experimentally, is 27%; also, power losses between the analytical output and the experimental results are 33.5% for the winter angle and 31.8% for the summer angle. On day 2, it was found that the power difference between the winter angle and mid-angle analytically is 2.29% and experimentally is 10.17%. Also, power losses between the analytical output and the experimental results are 30.3% for the winter angle and 35.9% for the mid angle. On day 3, it was found that the power difference between the mid-angle and summer angle, analytically, is 9.4% and experimentally is 9.3%; also, power losses between the analytical output and the experimental results are 26.7% for the mid-angle and 26.6% for the summer angle. Day 3 has the same difference analytically and experimentally, as both mid and summer angles are incorrect for winter.

Table 4

Difference table of output powers

DIFFERENCE IN OUTPUT POWER (%) FOR DAY 1		
Analytical	Winter vs summer angle	19%
Experimental	Winter vs summer angle	27%
DIFFERENCE IN OUTPUT POWER (%) FOR DAY 2		
Analytical	Winter vs Mid angle	2.29%
Experimental	Winter vs Mid angle	10.17%
DIFFERENCE IN OUTPUT POWER (%) FOR DAY 3		
Analytical	Mid vs summer angle	9.4%
Experimental	Mid vs summer angle	9.3%

The observed difference between the analytical and experimental results is due to the model's assumption of ideal conditions, excluding external factors such as dust accumulation, shading, and temperature variations. This study also focuses on the impact of the evaluation of tilt angle in different seasonal conditions on PV panel power output. Future work can be done to determine the combined effect of dust, shading, temperature, and tilt angle on the output power of the PV module.

6. CONCLUSION

This study concludes by estimating the performance of PV panels. The tilt angle of PV panels is a crucial factor affecting their output power, which varies depending on how much radiation the earth receives throughout the year. Fixed tilt angles may cause decreased performance of the photovoltaic panel. The analytical results show that the winter *vs* summer angle shows a significant power output difference of 19%. Similarly, analytical calculations also depict that winter vs mid-angle shows a difference of 2.29%. Both analytical and experimental approaches have been employed to investigate the effect of fixed tilt angles, revealing that positioning the panels at +15° above latitude in the winter and –15° below latitude in the summer can enhance their efficiency and output power. A significant amount of power output has been decreased due to the incorrect inclination of a PV panel. However, due to a disparity between analytical calculations and experimental measurements to optimize the performance of PV panels, it is advisable to place them according to the recommended angles.

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CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Muhammad Ammad, M. Faisal Khan, and Basit Ali were involved in the study's conception and design.

M. Faisal Khan and Basit Ali collected data, while the analysis and interpretation of results were jointly conducted by Muhammad Ammad, M. Faisal Khan, and Basit Ali.

Muhammad Ammad and Basit Ali prepared the draft manuscript. All authors reviewed the results, provided critical revisions, and approved the final version of the manuscript.

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