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A Case Study on Optimal Tilt Angle and Spacing for Rooftop Solar Photovoltaic System at Bhubaneswar

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ABSTRACT

The effectiveness of photovoltaic (PV) surfaces in capturing solar energy is influenced by the angle at which sunlight strikes them. To maximize irradiance collection, PV modules should ideally be positioned perpendicular to incoming solar rays. Suboptimal placement can result in diminished system performance, highlighting the importance of installing PV modules at an ideal tilt. Additionally, shadow effects can significantly impact PV array efficiency. This research examines key aspects of PV system installation, with a focus on array positioning in terms of tilt angle and row spacing to reduce horizontal shading. When installing PV arrays, determining the optimal tilt angle is essential for maximizing irradiance reception. Row spacing is calculated to eliminate inter-array shadows. The study presents calculations for optimal tilt angle and spacing, validated through a prototype 11.2 kWp solar photovoltaic system installed at Siksha 'O' Anusandhan, Bhubaneswar, India. The research determines monthly and yearly optimal tilts, solar flux gains, and energy yields for this specific location. Findings show a maximum solar flux gain of 32.97% in December, with a Global Solar Radiation (GSR) of 4.72 kWh/m2/day at a 40° optimal tilt. The lowest solar flux gains are observed in July, August, and September. Tilt adjustments during summer months (May to August) increase shading, which contributes to cooling effects.

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1. INTRODUCTION

The growing energy needs of households and industries are pushing traditional power sources beyond their limits, significantly increasing environmental pollutants. Solar energy offers a potential solution to reduce reliance on conventional sources like coal, thereby decreasing greenhouse gas emissions. The abundant availability of solar energy on Earth's surface makes it an ideal candidate to address the global energy crisis. In India, over 90% of regions receive average solar insolation ranging from 3.0-6.5 kWh/m2/day (10.8-23.4 MJ/m2/day) during summer, as illustrated in Fig.1 [1]. Some northern parts of India experienced solar insolation up to 7.5 kWh/m2/day (27 MJ/m2/day) in May [2]. Solar irradiance has been harnessed for various applications, including solar thermal systems, cookers, water heaters, photovoltaics (PV), daylighting, building heating, and crop drying. Numerous studies have been conducted to maximize the utilization of solar irradiance.

Solar photovoltaic (PV) technology stands out as a prominent method for converting solar irradiance into electricity through the photoelectric effect [48]-[49]. The power output of PV systems is directly proportional to the amount of solar irradiance incident on their surface [50]. Factors such as orientation, location, climate, latitude, tilt angle, geographical region, azimuth angle, and positioning significantly influence PV system performance [3]. Various shading conditions can impact power generation, but these effects can be mitigated using different topologies [4]. The performance of solar photovoltaic systems has been extensively discussed in [5]-[7].

The tilt angle (β) is a crucial factor in photovoltaic (PV) systems, determining the amount of solar radiation captured by the PV surface. While solar tracking devices can enhance PV system performance by following the sun's path to maximize irradiance reception [8, 9], they come with drawbacks. These devices require either servo motors or manual adjustments, which can be impractical due to frequent angle changes throughout the day, season, and month. Research has shown that inclined tracking systems demand approximately 350% more space (6.94 ha), and two-axis tracking systems need about 550% more area (4.81 ha) compared to static PV modules occupying 1.08 ha [10]. Furthermore, automatic solar trackers consume 6-12% of the total energy produced for their operation [11]. The motors need regular maintenance and replacement, increasing system costs. The complex moving parts in trackers also raise the initial investment and overall energy production expenses [12]. Researchers have proposed various methods to optimize flat surface orientation at the optimal tilt inclination (βopt). Experimental studies have compared PV systems with and without sun tracking [13], revealing a slight average increase in power generation for tracked systems. Other research has demonstrated that weekly horizontal axis adjustments combined with continuous vertical axis adjustments can yield marginally more energy than fixed-tilt PV systems [9]. To maximize PV system efficiency, tilt angle adjustments can be made hourly, monthly, seasonally, bi-annually, or annually [11].

Generally, PV systems in the northern hemisphere are oriented due south (γ=0°), while those in the southern hemisphere face due north, tilted at a specific angle to maximize annual solar irradiance capture. The surface azimuth angle is represented by 'γ'. Research has shown that the optimal tilt angle (βopt) is influenced by latitude (ϕ) and azimuth (β) [12] –[13]. When precise information on the optimal tilt angle is unavailable, various rules of thumb are employed [14]. Studies indicate that adjusting the azimuth angle by 10-20° and setting the tilt angle equal to the location's latitude can effectively track maximum solar irradiance [3]. However, these methods may not be reliable as they can deviate from actual values. Numerous studies have examined the optimal tilt angle for European countries [15]-[38]. Methods for maximizing solar irradiance by adjusting the optimal inclination angle are explored in [39]-[41].

Research on optimal tilt angle estimation for India using the Liu & Jordan model suggests that the yearly optimal tilt angle approximates the location's latitude. The authors recommend a tilt angle of (ϕ-16°) during summer and (ϕ+19°) in winter. A comparison of measured solar irradiance data with various anisotropic and isotropic models for inclined surface solar irradiance estimation in Bhopal, India (23°17'N, 77°36'E) concluded that the Badescu model provides the most accurate estimation with minimal statistical errors [42]. Statistical analysis and comparison of diffused solar irradiance on tilted surfaces using different models for Lucknow, India (26.75°N, 80.50°E) determined that Klucher's model offers the best estimation [43] - [44]. Multiple studies have identified the Liu & Jordan isotropic model as the most widely used approach for estimating solar irradiance at a given location. Research has also been conducted on solar radiation estimation and optimal tilt angles for south-facing surfaces in India's humid subtropical climatic region [42]. In

India, most photovoltaic (PV) arrays are positioned on flat building roofs to maximize solar exposure and energy production throughout the year. Although mutual shading between PV modules or arrays can decrease power output, this issue is often overlooked and has limited solutions [46]. The impact of mutual shading is frequently estimated rather than calculated and is considered a significant factor in power loss, accounting for up to 15% annually in PV systems [43-46]. The extent of mutual shading is heavily influenced by the arrangement of PV modules or arrays and system characteristics such as series/parallel connections and bypass diode placement.

This research employs a mathematical method implemented in MATLAB to determine the ideal angle of inclination for different months and seasons in Bhubaneswar, India. The investigation aims to establish the yearly tilt angle for the city, ensuring that photovoltaic modules or arrays installed in the area receive maximum solar radiation throughout the year, thereby maximizing electricity production. Additionally, the study proposes an optimal spacing between PV modules or arrays to minimize mutual shading effects. These approaches are validated through a prototype rooftop PV system installation.

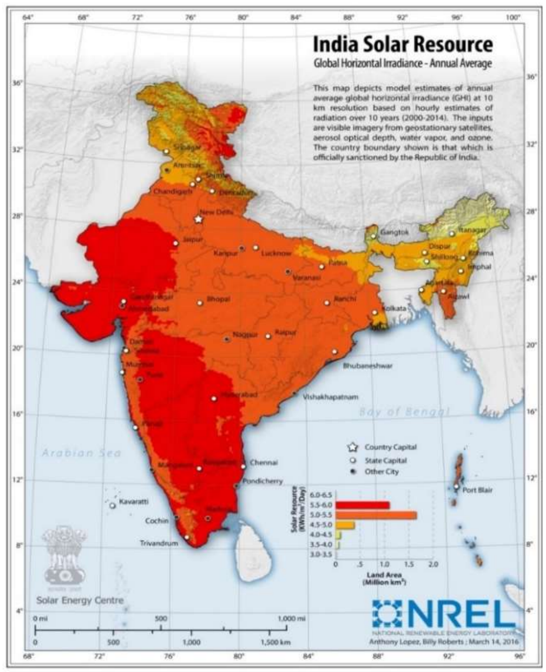

Fig. 1: Annual average global solar radiation in India [1].

As a rapidly expanding smart city in India, Bhubaneswar is ideally situated for solar energy exploitation, with coordinates of 20.2961° N latitude and 85.8245° N longitude. The city experiences significant solar potential, receiving an average global solar radiation (GSR) of 5-5.5 kWh/m^2/day, as depicted in Fig 1. Solar radiation in Bhubaneswar fluctuates throughout the year, reaching its zenith in April with 6.2 kWh/m^2/day and its nadir in August at 3.8 kWh/m^2/day. The monthly variation of GSR and calculated declination angle (δ) on the horizontal plane of Bhubaneswar is represented in Table 1.

Table 1. Monthly Variation of GSR and Declination Angle (δ) of Bhubaneswar.

Sl. No.	Month	Representative days Number	GSR of respective days	Declination angle (δ) (in degree)
1	January	17 (17th)	3.7	-20.9170
2	February	47 (16th)	4.17	-12.9546

3	March	75 (16th)	4.84	-2.4177
4	April	105 (15th)	4.93	9.4149
5	May	135 (15th)	4.28	18.7919
6	June	162 (11th)	3.43	23.0859
7	July	198 (17th)	2.94	21.1837
8	August	229 (17th)	3.81	13.1224
9	September	258 (15th)	3.43	2.2169
10	October	288 (15th)	3.73	-9.5944
11	November	318 (14th)	3.66	-18.9120
12	December	344 (10th)	3.43	-23.0496

2. SYSTEM SETUP

For Bhubaneswar city, calculations have been made to determine the tilt angle across various months, seasons, and on an annual basis. These findings have been verified using an 11.2 kWp Solar PV system installed on the rooftop of the E-Block at ITER, Siksha 'O' Anusandhan Deemed to be University in Bhubaneswar. To prevent mutual shading, the necessary spacing between PV arrays was computed for the installed system. Fig 2 illustrates the configuration of the 11.2 kWp rooftop PV system.

The setup has been installed at a specific tilt angle, with spacing determined using the mathematical model's calculated values outlined in Section 2. The configuration comprises two parallel-connected strings, each containing twenty PV modules connected in series, generating a total power output of 11.2 kW. Details regarding the PV module specifications and system dimensions are provided in Table 2 and Table 3, respectively. With a fixed inclination of 22.5 degrees, the photovoltaic installation occupies a total surface area of 101 square meters.

Table 2: Specification of PV Module at STC (1000W/m^2 and 25^{O}C)

Parameters	Rating
Maximum Rated Power (Pmax)	280 W
Open Circuit Voltage (V_{OC})	43 V
Short Circuit Current (I_{SC})	8.68 A
Voltage at Maximum Power Point (V_{MP})	35 V
Current at Maximum Power Point (I_{MP})	8 A
PV modules in series connection	20
strings in parallel connection	2

Fig. 2: Setup of rooftop-based 11.2 kW PV system at Siksha 'O' Anusandhan Bhubaneswar Campus.

Table 3: Dimensions of PV Modules and Array.

Parameter	Dimension
Dimensions of the photovoltaic (PV) module	99 cm
Width of the PV module	196 cm
Length of the PV string	2000 cm

3. RESULTS AND DISCUSSIONS

The ideal orientation angles for PV modules/strings to maximize solar irradiance capture throughout the year are determined by the solar angle and the geometrical characteristics of the PV modules/string. These factors vary based on the time of day, month of the year, and geographical location. This study calculates tilt angles considering two approaches:

- Adjusting the tilt angle monthly.
- Maintaining a constant tilt angle year-round

3. 1. Monthly adjustment of tilt angle

Figure 3 displays the simulation graph between the tilt angle (β) and GSR on an inclined surface for every month throughout the year.

Table 4**.** Percentage of Annual Solar Flux Gain at flat and inclined surface.

Sl. No	Month	GSR on a horizontal plane	Monthly Optimum Tilt angle	GSR on Optimum Tilt Angle	Solar Flux Gain in %
1.	January	3.7	40°	4.92	32.97
2.	February	4.17	32.5°	4.98	19.42
3.	March	4.84	22.5°	5.25	8.47
4.	April	4.93	10°	5.01	1.62
5.	May	4.28	10°	4.51	5.37
6.	June	3.43	0°	3.43	0
7.	July	2.94	0°	2.94	0
8.	August	3.81	7.5°	3.81	0
9.	Sept	3.43	17.7°	3.61	5.24
10.	Oct	3.73	30°	4.30	15.28
11.	Nov	3.66	42.5°	4.72	28.96
12	Dec	3.43	40°	4.72	37.60

Calculations were performed to determine the Annual Solar Flux Gain on horizontal, monthly optimum tilted, and fixed tilted planes. The results revealed that monthly adjustment of solar panels yields approximately 13 percent more gain annually, compared to a 4 percent annual gain when panels are kept on a horizontal surface, as shown in Table 4. Furthermore, Table 5 illustrates that when comparing panels placed at monthly optimum tilt versus fixed tilt annually, the former resulted in a 4 percent increase in solar flux gain. These findings suggest that adjusting the Solar PV array to the calculated monthly optimum tilt angle will enhance system efficiency.

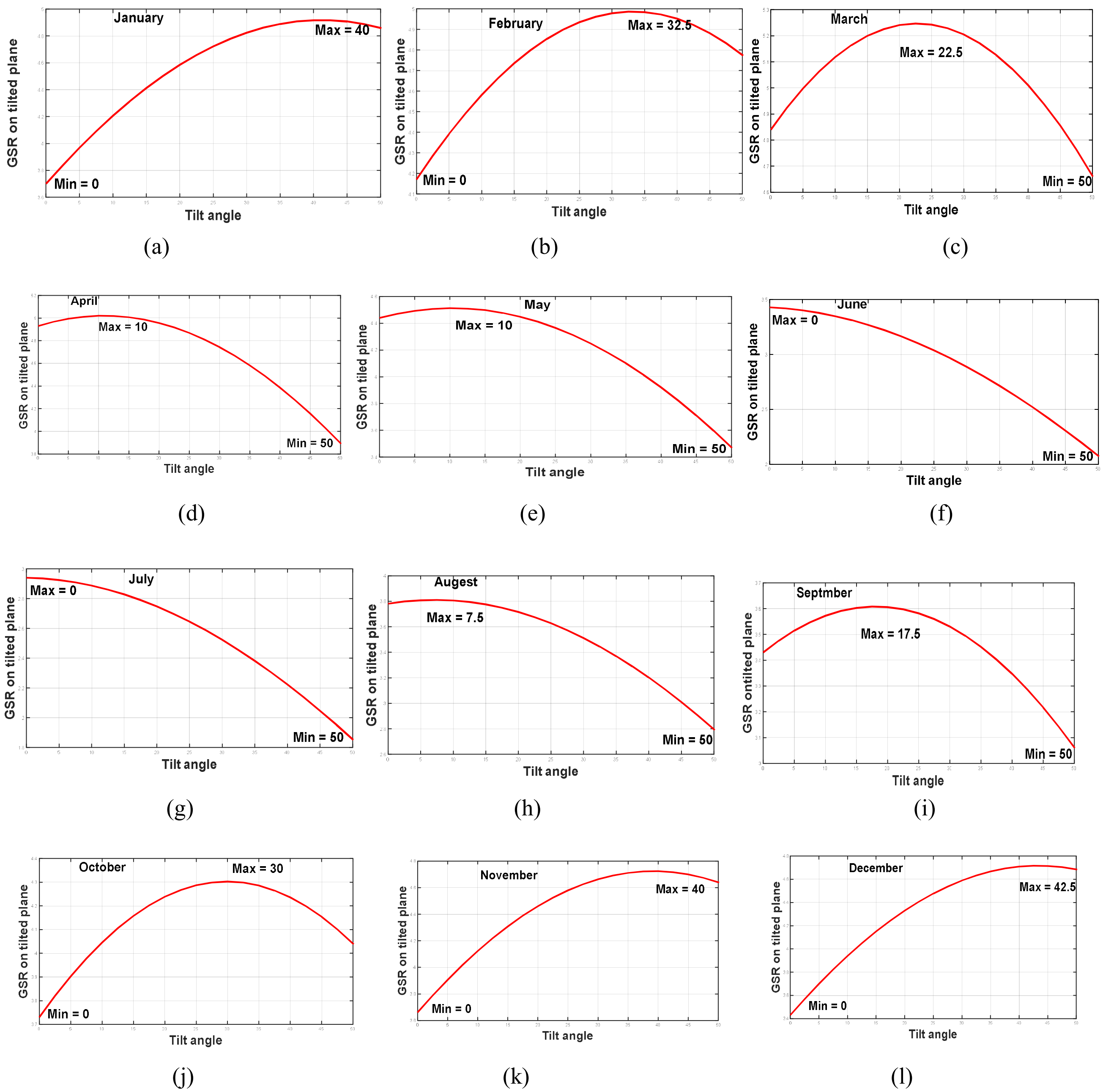

Fig. 3: Impact of adjusting the tilt angle on average GSR across various months throughout the year of (a) January (b) February (c) March (d) April (e) May (f) June (g) July (h) August (i) September (j) October (k) November and (l) December.

3 .2 Fixed tilt angle (annually)

The study examines the relationship between the tilt angle (β) and global solar radiation (GSR) on a fixed tilted plane throughout the year. Researchers discovered that when β remains constant, they could determine the tilt angle and GSR on the inclined surface. Fig 4 illustrates the annual fixed optimum tilt angle derived from this analysis. According to simulated calculations, the maximum Global Solar Radiation (GSR) received by a PV surface in Bhubaneswar is 4.20 kWh/m^2/day. This optimal GSR is achieved when the fixed tilt angle is set at 22.5 ^{0} [47].

Table 5: Percentage of Annual Solar Flux Gain at Fixed Plane and Optimum Tilted Plane.

Sl. No	Month	GSR on Fixed Tilted Angle (22.5^0)	GSR on Optimum Tilt Angle	Solar Flux Gain in %
1	January	4.65	4.92	5.80
2	February	4.89	4.98	1.84
3	March	5.24	5.25	0.19
4	April	4.91	5.01	2.03
5	May	4.41	4.51	2.27
6	June	3.10	3.43	10.64
7	July	2.7	2.94	8.89
8	August	3.70	3.81	2.97
9	September	3.6	3.61	0.28
10	October	4.26	4.30	0.94
11	November	4.52	4.72	4.42
12	December	4.40	4.72	7.27

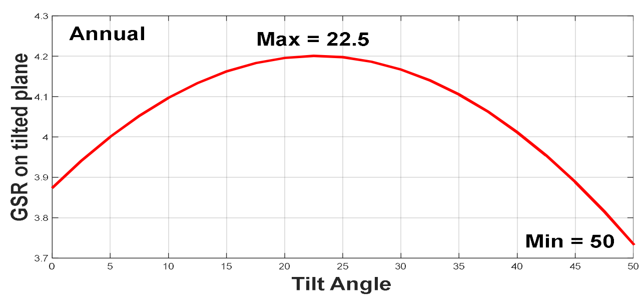

Fig. 4: Annual fixed optimum tilt on mean GSR.

3.3. Optimum Spacing for PV modules/strings

This section determines the ideal distance between PV modules or strings to prevent mutual shading. Calculations for an 11.2 kWp on-grid system installed at a fixed tilt angle have been performed to establish this spacing. The spacing also corresponds to the PV modules' shadow length during specific time periods. The maximum shadow length of the PV modules has been computed for various months, and the spacing has been adjusted accordingly. Table 6 displays the maximum shadow length of the PV modules for the 11.2 kWp system monthly.

3.4 Shadow Formation Monthly Adjustment of Array

The percentage of shadow found in monthly and annual adjustments of arrays is given by (1).

$$S = \left(\frac{S_i - S_j}{S_j} \right) \times 100 \tag{1}$$

In (1), S is the percent of shading, Si shading due to the optimum tilt angle and Sj is the Shading due to the fixed tilt angle of SPV arrays.

Table 6. Shadow formation of 11.2 kW PV system.

Sl. No	Month	Shadow Length/ Spacing (in cm) at optimum tilt (S_i)	Shadow Length/ Spacing (in cm) at fixed tilt (S_j)	Shading (%)
1	January	260.5	246.77	5.56
2	February	234.35	230.26	1.77
3	March	212.48	212.48	0
4	April	199.56	195.50	2.07
5	May	193.92	183.05	5.94
6	June	196	177.42	10.47
7	July	196	179.92	8.94
8	August	197.54	190.52	3.68
9	Sept	206.17	205.57	0.29
10	Oct	226.08	224.20	0.84
11	Nov	252.92	242.27	4.39
12	Dec	269.49	251.87	6.99

Research has shown that when a photovoltaic (PV) system is set at a constant 22.5^0 tilt angle year-round, the maximum shadow length reaches 269.45 cm in December. Consequently, to avoid shading issues, the minimum distance between PV strings should be no less than 269.45 cm.

Table 7. Electrical energy yield in all months of the year.

Sl. No.	Month	Energy Yield in kWh
1	January	1339.28
2	February	1376.09
3	March	1614.53
4	April	1462.86
5	May	1491.99
6	June	1141.41
7	July	1044.62
8	August	1202.04
9	Sept	1143.65
10	Oct	1336.38
11	Nov	1290.03
12	Dec	891.58

Table 7 presents the energy output from the 11.2 kWp photovoltaic (PV) installation for a typical day in each month of the year, as measured by Wattmon and Delta Solivia Monitor 2.0 software. The on-grid system examined in this study is positioned at a fixed 22.5° tilt angle, which was determined through computational analysis. This angle is considered optimal for the installation site in Bhubaneswar. A device called Wattmon was employed to record the voltage produced by the 11.2 kWp system hourly. The Delta Solivia Monitor 2.0 software was utilized to document all power generated by the PV system from January onwards, as captured by the Wattmon device.

4. CONCLUSION

Adjusting the inclination of a photovoltaic (PV) system can enhance the global solar radiation (GSR) received by its surface, thereby improving power generation. The optimal tilt angle varies monthly due to Sun position changes. This study estimates monthly and annual optimal tilt angles for Bhubaneswar, the capital smart city of Odisha, India. The distance between PV modules/strings has been calculated to prevent mutual shading and meet spacing requirements. These optimal tilt and spacing parameters were applied to install an 11.2 kWp on-grid PV system. The research yielded the following results:

i. Adjusting PV panels to monthly optimal tilt angles increased GSR and Solar Flux Gain by 13 percent annually compared to horizontal placement and fixed tilt (22.50).
ii. Horizontal placement of PV panels resulted in a 4% annual solar flux gain. Bhubaneswar's annual optimal tilt angle (βopt) is 22.5^0, approximating the location's latitude (20.29^0). This configuration yields an annual solar flux gain of about 9 percent.
iii. Research has shown that when photovoltaic (PV) panels are adjusted to monthly optimum tilt angles, they capture 4 percent more solar flux than panels fixed at a single annual tilt angle.
iv. The required distance between PV modules or strings is heavily influenced by shadow length, which varies throughout the day and depends on the size of the PV modules used.
v. To avoid shading, the spacing should exceed the maximum shadow length. For instance, the 11.2 kWp system in Bhubaneswar has a fixed spacing of 251.8 cm. However, monthly adjustments increase shading during May, June, July, and August, cooling the building while boosting power generation.
vi. The fixed tilt configuration requires 101 square meters, while the optimum tilt setup needs 108 square meters, an additional 7 square meters.
vii. With a fixed tilt angle, the system's annual energy yield is 15335 kWh. This output can be increased by adjusting the tilt angle of the Solar PV system.

It is advised to adjust the tilt angle monthly to maximize the Global Solar Radiation (GSR) received by the PV surface, thereby increasing electrical energy production. This approach also offers a cooling benefit during summer months (May, June, July, August). Shading increases by 5-6% in May 10-11% in June 8-9% in July, and 3-4% in August, effectively providing space conditioning for the building during summer while enhancing the system's efficiency.

DECLARATIONS

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