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# ESTIMATION OF SOLAR PHOTOVOLTAIC GENERATION YIELD BASED ON ROOFTOP TILT ANGLE

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**Abstract**

Solar photovoltaic (PV) based power systems are being deployed more often in order to satisfy increasing energy requirements and global decarbonisation campaigns. Precise estimation of PV yield is essential for sizing systems, performance optimization and long-term planning. One limitation of existing models, including the Sustainable Energy Development Authority (SEDA) Malaysia formula, is that it does not provide a good approximation to different roof slopes and orientations. As a result, this led to less accurate performance estimates e.g. on tilted or multi-roof-top plate configurations. As such, this paper proposes a better method for predicting PV output by generating accurate factors and fitting formulas with respect to roof tilt and azimuth. LossFactor models were produced using PVSyst for different tilt and azimuth settings for all the Malaysian state capitals. Key parameters including global irradiance and temperature dependence, as well as module and system losses were deduced to study the influence of geometrical parameters on overall performance. Tilt angles ranging from 0° to 60° and azimuth orientations of south, east, and west were analyzed. A polynomial-based predictive model using a compiled data set was developed to estimate the optimal tilt–azimuth pairs for an annual energy production. The accuracy of the model was validated through on-site measurements and this model was consistent with the simulation output. Many researchers state a consistent and significant interaction between roof structure and the PV efficiency, where the improvement in energy output deviations resulting in measurable losses was determined by the optimal configuration. This study introduces a robust and practical method to enhance PV yield estimation through integration of simulated data, mathematical modelling and field validation.

**Keywords**: Solar Photovoltaic sizing; rooftop tilt angle; azimuth; power loss; PVSyst



## 1.0 INTRODUCTION

In the present day, the shift to sustainable energy has significantly increased the application of solar photovoltaic (PV) to meet the demand for energy and conquer the environmental issues associated with traditional energy production. This demand is increasing due to rapid urbanization, industrialization and intensified electrification in both residential and commercial areas. PV systems help to mitigate GHG (greenhouse gas) emissions, reduce dependence on the use of non-renewable sources of energy and meet sustainable development goals. Accurate prediction of PV energy output is vital to optimize the operation and maintenance of tidal current generation systems, as it has a direct impact on the system design parameters, energy management strategies and investment studies [1],[2]. Also, reliable forecasting can help stakeholders properly size solar systems, determine the components to be selected, project financial returns and integrate its system within the power grid. The output from PV is affected by several factors which include tilt angle, azimuth orientation, temperature, solar irradiation and roof types. Tilt angle and azimuth orientation are especially important, since they determine the solar radiation directly incident to PV panels and consequently influence system power output [3]. Tilt angle is the angle of the PV panel with respect to horizontal plane, which determines how much sunlight can be incident on the surface and affects energy generation [4]-[8]. On the contrary, azimuth angle is the compass direction of panel inclination which varies throughout day to adjust solar exposure and peak irradiation hours [7],[9],[10]. These two factors combined strongly determine the amount of energy a PV system can harvest, especially on rooftops where orientation is typically fixed.

From the previous research, the parameters that influence PV performance were essentially dependent on the tilt angle and azimuth direction, since the direct beam solar radiation and the consequent energy yields were influenced by the configurations. Tamoor et al. [4] revealed that a small deviation from the optimal angle can significantly reduce the energy produced by experimented PV modules at different tilt angle and orientations, showing the sensitivity of PV performance to installation angle. Mamun et al. [8] and Masrur et al. [6] showed that appropriate tilt angles change not only with latitude but also with seasonal variation in solar path, fluctuation in temperature and local weather condition by also illustrated the significance of tilt optimization by assessing PV performance in a variety of climates. Dimd et al. [7] stated the significance of enhancement in in-plane capture of solar irradiation, which contributes to higher energy generation efficiency by focused on the orientation angle in azimuth direction and indicated that aligning with the optimum compass direction of panels.

Moreover, predictive models such as those established by Obiwulu et al. [10] and Mansour et al. [11] discussed the possibility of determining optimal tilts in limited area through seasonal and local irradiance data using quantitative method. These approaches lead to better design and precise energy estimation of PV systems adapted to the respective regions. Memme and Fossa [12], Oh et al. [13], as well as Yadav and Bajpai [14] improved this analysis by taking in other practical aspects such as roof type, shadow effects and actuality of installation of the PV panels to infer that away from ideal tilt and azimuth results in lower expected power output on an annual basis with decreased efficiency. All these works together, emphasis that high PV systems performance can only be attained through accurate tuning and selection of the optimum tilt angle and azimuth angle respectively, those contribute on solar harvesting, energy yield and long-term operational efficiency. The results of the study imply that empirical models based on both parameters are necessary to achieve a reliable forecast with respect to PV performance and system optimization.

However, to date there was still a shortage in comprehensive approaches forming empirical coefficients or predictive equations that include both tilt angle and azimuth orientation for sensitive-yield estimation of PV system with respect to Malaysia. Existing work concentrates on isolated contributors or region outside Malaysia, and provide limited practical aids for rooftop PV installations in Malaysian state capitals. Although efficiency, tilt and orientation are being frequently discussed in the literature of solar radiation availabilT it has yet to include empirical coefficients that can be applied according to the respective site conditions in Malaysia. This gap in research is especially precarious, given that the existing models to predict output of such photovoltaic energy generation (including those used as a default method by the Sustainable Energy Development Authority Malaysia (SEDA)) fail to consider the co-acting effect of both tilt and azimuth angles. As a result, such methods may predict inaccurately and result in suboptimal solar resources utilization which is a particular case for places with wide variety of climatic and geographical location [4], [5].

## 2.0 METHODOLOGY

The research approach places attention on deepening the analysis of the power loss behaviour of PV systems with emphasis on development and refining of coefficients/models used for improved output estimation. The effect of tilt angle and the azimuth orientation to enhance the energy yield in Malaysia's capital cities is discussed. The parametric values are extracted in PVSyst software, supported by real experimental works and measurements on field. After collecting the data, such data is analyzed and tabulated, and empirical equations are derived which will allow one to take full advantage of a photovoltaic system.

### 2.1 Data Collection

A popular simulation tool for modelling PV system performance, PVSyst, was used to extract data. To simulate performance results realistically, crucial input conditions were set in the software such as geographical position, angle of mounting, solar energy available and the prevailing air temperature. The study included all state capitals of Malaysia to obtain geographical variation. To make it possible for an in-depth assessment of the spatial dependence of PV yield, a wide variety of climate and environmental conditions were included.

PV module power degradation behaviour is remarkably influenced by effects of site-specific parameters, such as solar insolation level, temperature fluctuation and potential shading conditions were studied extensively. Tilt angles ranged from 0° to 60° and azimuth orientations included all the cardinal and intercardinal directions (N, NE, E, SE, S, SW, W and NW). The arrangement of tilt and azimuth settings in PVSyst is illustrated in Figure 1. This systematic set-up made it possible to compare effect of orientation and inclination on PV output in various regions in Malaysia. For every location, we simulated different tilt angles of the plane (from 0° to 60°) and azimuth orientations (north -N-, northeast -NE-, east -E-, southeast -SE, south -S- to southwest) from eight cardinal and intercardinal directions). Figure 1 shows the choices of plane tilt and azimuth orientations. This systematic simulation provided a holistic approach to investigate the impact of tilt and orientation on energy yield in Malaysia.

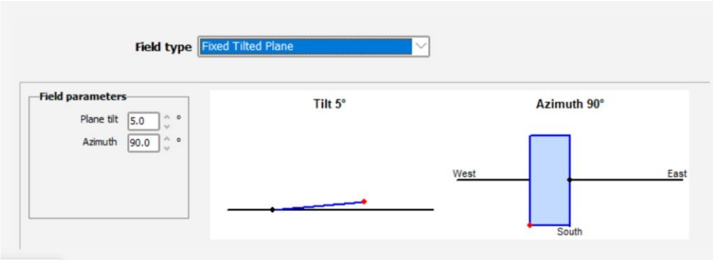


**Figure 1** Selection of Plane Tilt and Azimuth Orientation

### 2.2 Development of Power Loss Equation

The simulation data set is used to generate a polynomial equation on power loss as a function of tilt angle, azimuth orientation, solar irradiation and other respective environmental variables. To account for the nonlinear, coupled interactions between these parameters polynomial regression was fitted. This strategy allowed the mathematical equation to truly represent the change of the system losses based on different installation conditions.

The obtained equation can be used as a predictive model for the power loss calculations in many kinds of PV systems. Using design parameters and environmental factors installers can calculate the optimal installation angle, which can reduce loss and improve overall power production. The dataset was also inspected for any anomalies during the modeling and consistency violations were corrected or anomalies were removed to enhance our regression results and assure that the fitted model is robust.

### 2.3 On-site Measurement and Validation

On-site experiments were performed on power loss model, the relationship of parameters wascalculated to verified the novel formula PV150 meter and irradiance meter, which are a reference device so that reliabilitycalibration curve can be achieved as in Figure 2. The PV150 recorded instantaneous module voltage and current, the irradiance meter measured real time solar irradiance. These measurements were necessary to evaluate the real operating behaviour of the PV system under real weather conditions.


**Figure 2** The irradiance meter (left) and PV150 (right)

Moreover, besides data acquisition, our on-site measurements have confirmed the predicted power-loss values calculated by our proposed equation. The study examined how the model can represent actual performance by comparing estimated and measured losses. The field studies were conducted in Johor Bahru at different tilt (5°, 35°, and 45°) and azimuth (north, south, east, and west), as shown in Figure 3 Experiments were performed under diverse weather conditions to avoid the lack of diversity and robustness in validation. This holistic methodology increased confidence in the utility of this equation for fielded installations.

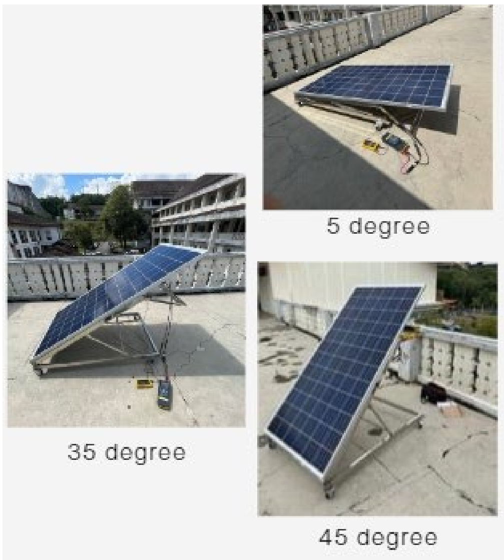


**Figure 3** On-Site Installation of Solar Panels at Different Tilt Angles

In order to enhance the accuracy of collected data, the SEDA empirical expressions are applied for estimating expected voltage according to equations (1-3), and current measurements result by these equations (4-6) is compared with field-measurements [20]. This comparison based on an additional reference was intended to verify the system under test, and deviations from this design value would indicate system non-uniformities or effects of ambient parameters.

$$k_g = \frac{G}{100} \tag{1}$$
$$k_{temp} = 1 + \left[\left(\frac{\delta}{100}\right)\right](T_{cell} - 25) \tag{2}$$
$$k_{temp-v} = k_{mm-v}(k_{temp}) \tag{3}$$
$$V_{expected} = V_{stc}(k_{temp-v}) \tag{4}$$
$$k_{current} = k_{mm-i}(k_{temp-i})(k_g)(k_{dirt}) \tag{5}$$
$$I_{expected} = I_{stc}(k_{current}) \tag{6}$$

Where;

$G$ - Global solar irradiance (W/m²) measured on the plane of array
$k_g$ - Irradiance correction factor, defined as the ratio of measured irradiance to the standard test condition (STC) irradiance (1000 W/m²)
$\delta$ - Temperature coefficient of the PV module (%/°C), typically provided by the manufacturer.
$T_{cell}$ - Solar cell operating temperature (°C)
$k_{temp}$ - Temperature correction factor applied to voltage or current depending on the context.
$k_{mm-v}$ - Temperature coefficient multiplier for voltage correction.
$k_{mm-i}$ - Temperature coefficient multiplier for current correction
$k_{temp-v}$ - Temperature correction factor specifically for voltage
$k_{temp-i}$ - Temperature correction factor specifically for current
$k_{dirt}$ - Soiling or dirt factor representing losses due to dust or surface contamination
$V_{stc}$ - PV module voltage under Standard Test Conditions (STC)
$V_{expected}$ - Expected operating voltage after applying correction factors
$I_{stc}$ - PV module current under Standard Test Conditions (STC)
$I_{expected}$ - Expected operating current after applying correction factors

Analysis and verification of the two categories was in three main stages. Using data generated for all state capitals by PVSyst, a complete simulation study was made throughout the wide range of tilt angles and azimuth orientations. Secondly, coefficients defining power loss equation was estimated by polynomial regression. The resultant model was verified with measured data and compared to SEDA's empirical formula, indicating the reliability and practical applicability of it. This systematic approach yielded a comprehensive knowledge base of PV power degradation patterns, validated predictive equation and accurate estimation of PV system performance in wide variety of geographical and environmental conditions.

## 3.0 RESULTS AND DISCUSSION

The Comprehensive analysis of the simulation results and comparison with empirical data are discussed in this chapter and concluded with an integrative discussion of the findings. The impact of investigation of some critical installation criteria to review the case studies such as such as tilt angle and azimuth orientation on PV system performance. in different environmental and geographical conditions. In the different environmental and geographical conditions, the identification and assessment of possible variables and their contribution to power loss was concentrated by these case studies. The gaps and align our overall understanding of PV performance sensitivity across Malaysian state capitals were filled by the findings of these analyses. The results bring out trends, correlations and performancevariance with the installation geometry and contribute towards a broader objective of helping to optimize PV system configuration for minimizing losses and maximising energy yield.

### 3.1 Simulation Results

PVSyst facilitated loss diagrams for Johor Bahru with tilt angles of 0° and 60° are shown in Figures 4 and 5, respectively. A significant power loss increase is also realised at 60° tilt angle as a consequence of lower incident global radiation on the collector plane. The comparison shows that the PV output sensitivity to tilt angle is quite accurate, and it is necessary to choose an optimal inclination or tilt angle in order to minimize the energy loses.

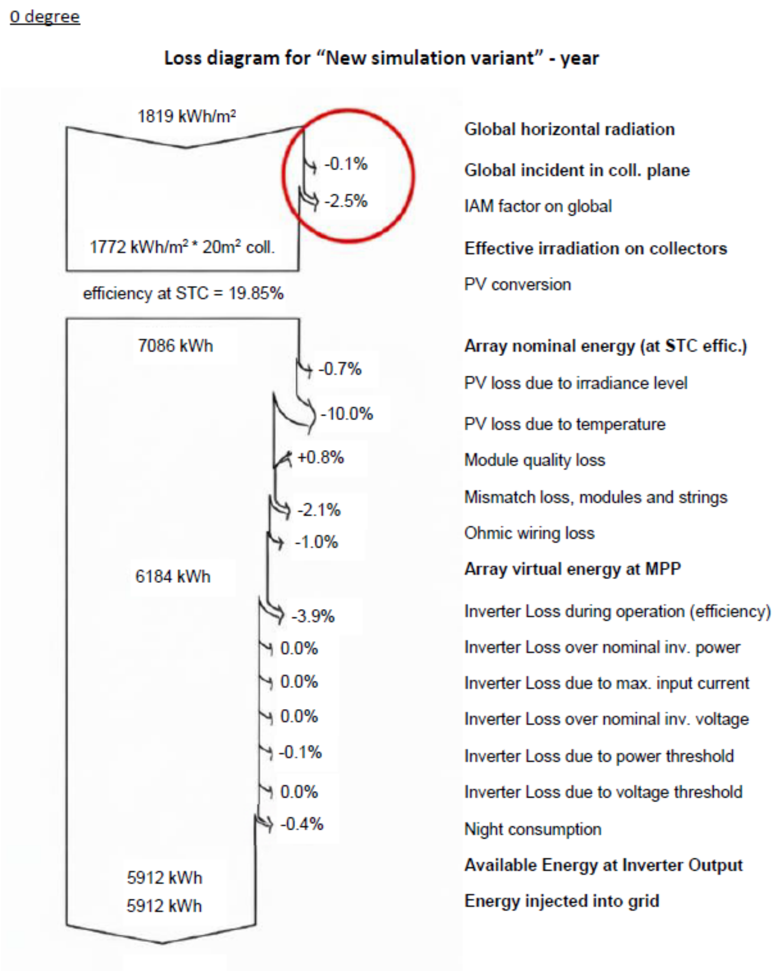


**Figure 4** Power Loss Profile for Photovoltaic Panels at 0° Inclination

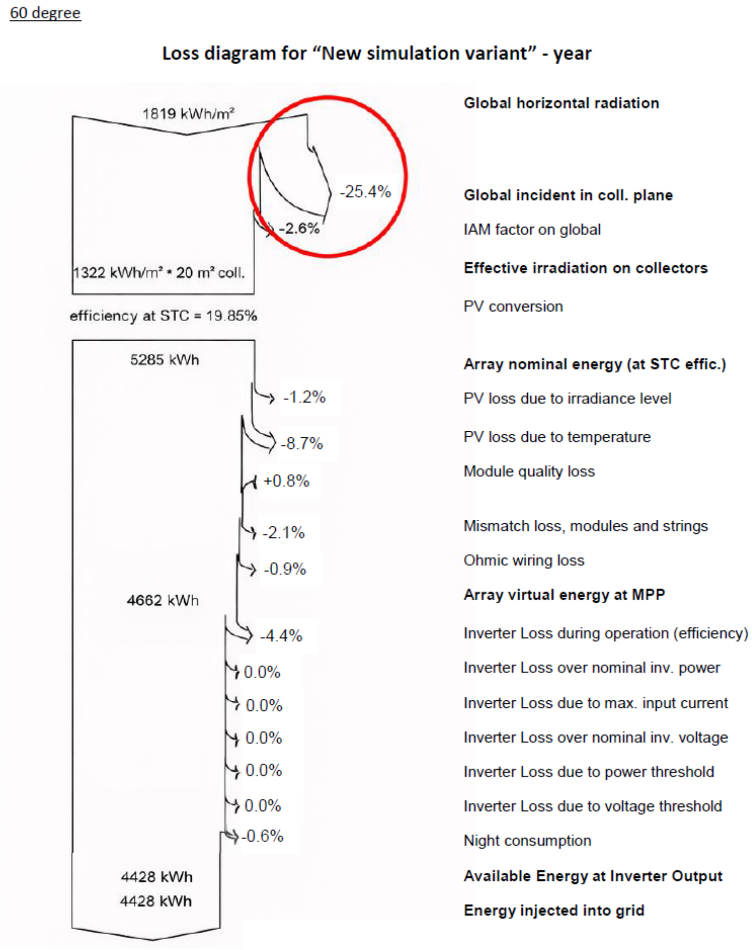


**Figure 5** Power Loss Profile for Photovoltaic Panels at 60° Inclination

Table 1 shows the percentage power loss for tilt angles between 0° and 60° at eight azimuth positions. The data show a continuous rise of loss with rising tilt, reaching above 30% at 60° for some orientations. At the lower tilt angles (0°–10°), losses are still just marginal, due to sun path more favorable for Johor Bahru equatorial climate.

**Table 1** Impact of Tilt Angle and Azimuth Orientation on Power Loss in Johor Bahru

| Tilt Angle | Global incidentin coll. Plane [SOUTH 0] | Global incident incoll. Plane [SOUTH-WEST 45] | Global incident incoll. Plane [WEST 90] | Global incident incoll. Plane [NORTH WEST 135] |
|---|---|---|---|---|
| 0˚ | 0% | 0% | 0% | 0% |
| 1.5 ˚ (JB) | 0% | 0% | 0% | 0% |
| 5˚ | -0.1% | -0.1% | -0.1% | -0.2% |
| 10˚ | -0.8% | -0.8% | -0.8% | -0.8% |
| 15˚ | -2.0% | -1.9% | -1.8% | -2.0% |
| 20˚ | -3.7% | -3.6% | -3.4% | -3.6% |
| 25˚ | -5.9% | -5.6% | -5.2% | -5.6% |
| 30˚ | -8.6% | -8.1% | -7.3% | -8.1% |
| 35˚ | -11.7% | -11.0% | -9.9% | -11.0% |
| 40˚ | -15.3% | -14.1% | -12.5% | -14.1% |
| 45˚ | -19.4% | -17.6% | -15.4% | -17.5% |
| 50˚ | -23.7% | -21.3% | -18.6% | -21.1% |
| 55˚ | -28.3% | -25.1% | -21.8% | -24.9% |
| 60˚ | -33.2% | -29.1% | -25.1% | -28.8% |

| Tilt Angle | Global incident in coll. Plane [NORTH 180] | Global incident in coll. Plane [NORTH-EAST-135] | Global incident in coll. Plane [EAST-90] | Global incident in coll. Plane [SOUTH-EAST -45] |
|---|---|---|---|---|
| 0˚ | 0% | 0% | 0% | 0% |
| 1.5 ˚ (JB) | 0% | 0% | 0% | 0% |

| | | | | |
|---|---|---|---|---|
| 5˚ | -0.2% | -0.2% | -0.2% | -0.2% |
| 10˚ | -0.9% | -0.9% | -0.8% | -0.8% |
| 15˚ | -2.1% | -2.1% | -1.8% | -1.9% |
| 20˚ | -3.8% | -3.7% | -3.3% | -3.4% |
| 25˚ | -6.1% | -5.7% | -5.1% | -5.4% |
| 30˚ | -8.8% | -8.2% | -7.1% | -7.8% |
| 35˚ | -12.0% | -11.0% | -9.5% | -10.5% |
| 40˚ | -15.7% | -14.2% | -12.3% | -13.6% |
| 45˚ | -19.7% | -17.7% | -15.1% | -17.0% |
| 50˚ | -24.1% | -21.4% | -18.3% | -20.6% |
| 55˚ | -28.8% | -25.2% | -21.6% | -24.3% |
| 60˚ | -33.7% | -29.2% | -24.9% | -28.3% |

Figure 6 portrays the trend of power loss increment against higher tilt angle by noting of to exceed the optimal value in Johor Bahru. This optimum range differs by capital cities because of differences in their solar radiation spectrum, atmospheric profiles and shadings. For comparison, the relationship is portrayed in Figure 7 for Kangar with a slightly different pattern which further validated the mixing height coefficients should be developed specifically at each location to improve modeling prediction.

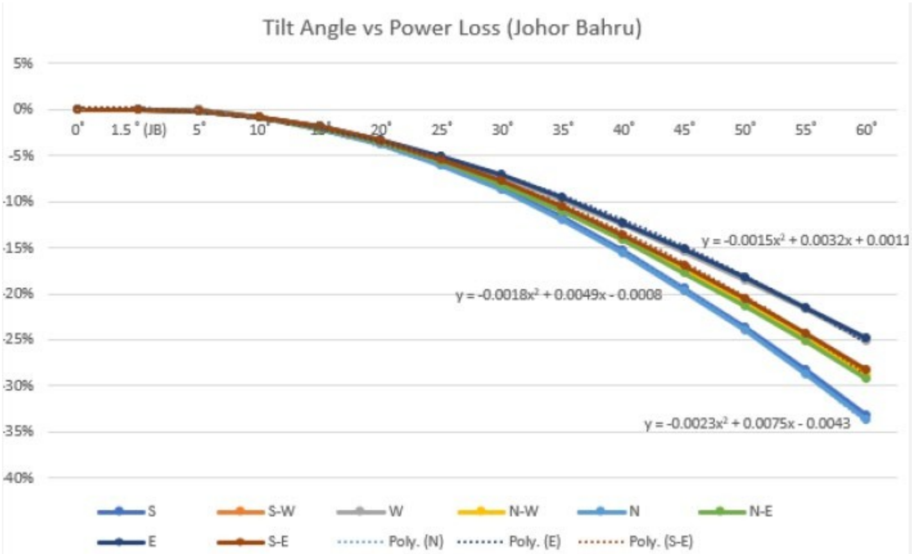


**Figure 6** Impact of Tilt Angle Variation on Power Output Loss in Johor Bahru

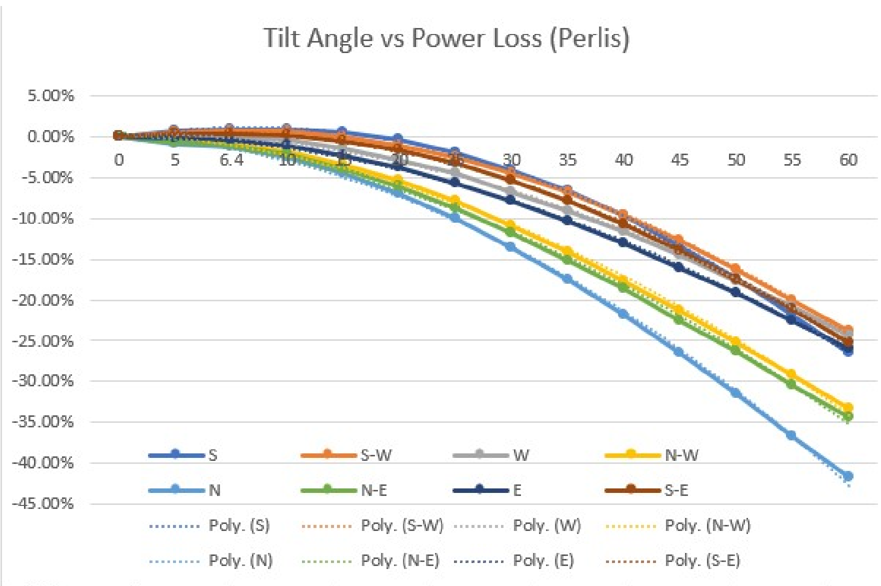


**Figure 7** Impact of Tilt Angle Variation on Power Output Loss in Kangar

These contrasts reveal the importance of locally aligned design parameters. For maximization of yielded energy and minimization of annual performance losses, these derived coefficients to optimize tilt and azimuth settings that are more representative of local climatic conditions can be utilized by the system designers.

### 3.2 Power Loss Equation

The coefficients of the power-loss to link distance equation for different azimuth orientations in Johor Bahru were obtained from polynomial regression. In Table 2, the second order polynomials coefficients ($x^2$ $x^1$, and $x^0$) for each orientation are given. These coefficients can be used to estimate expected power loss for any tilt angle in the range tested.

The equation is proposed as a useful and effective optimization approach for PV system engineers. Through plugging in orientation and inclination into the polynomial function, power loss can be estimated and best configuration can be chosen. Detailed coefficients allow for the optimization of the system design to reduce losses and increase energy production.

**Table 2** Power loss coefficients corresponding to multiple azimuth orientations in Johor Bahru

| Location | Facing Azimuth | $x^2$ | $x^1$ | $x^0$ |
|---|---|---|---|---|
| JOHOR (JOHOR BAHRU)[1.5 N] | S | -0.00009 | -0.00025 | 0.00202 |
| | S-W | -0.00007 | -0.00065 | 0.0033 |
| | W | -0.00006 | -0.00081 | 0.00345 |
| | N-W | -0.00007 | -0.0007 | 0.00319 |
| | N | -0.00009 | -0.00032 | 0.00189 |
| | N-E | -0.00007 | -0.00068 | 0.00284 |
| | E | -0.00006 | -0.00068 | 0.00261 |
| | S-E | -0.00007 | -0.00054 | 0.00254 |

### 3.3 On-Site Measurement

The derived polynomial model was validated onsite in Johor Bahru to assess its accuracy. Table 3 compares the anticipated power loss values to metered losses recorded by PV150 and irradiance meters at representative tilt (5°, 35°, 45°) and orientation (north, south, east west).

**Table 3** Comparison of actual power loss percentages versus calculated power loss

| Tilt Angle(Facing Azimuth) | P_plain (W) | P_measure(W) | Ploss_measure (W) | Ploss_measure (%) | Ploss_expected (%) |
|---|---|---|---|---|---|
| Panel 45 (FS) | 358.739 | 293.679 | 65.060 | 18.14 | 19.15 |
| Panel 45 (FW) | 355.200 | 306.667 | 48.533 | 13.66 | 15.45 |
| Panel 45 (FN) | 350.118 | 284.849 | 65.269 | 18.64 | 19.48 |
| Panel 45 (FE) | 341.045 | 289.294 | 51.751 | 15.17 | 14.95 |
| Panel 35 (FS) | 349.439 | 311.856 | 37.583 | 10.76 | 11.69 |
| Panel 35 (FW) | 358.036 | 327.120 | 30.916 | 8.63 | 9.84 |
| Panel 35 (FN) | 347.720 | 308.959 | 38.761 | 11.15 | 11.96 |
| Panel 35 (FE) | 355.492 | 320.572 | 34.920 | 9.82 | 9.47 |
| Panel 5 (FS) | 359.630 | 350.948 | 8.682 | 2.41 | 1.48 |
| Panel 5 (FW) | 355.609 | 346.845 | 8.764 | 2.46 | 2.10 |
| Panel 5 (FN) | 351.107 | 342.682 | 8.425 | 2.40 | 1.96 |
| Panel 5 (FE) | 386.797 | 377.496 | 9.301 | 2.40 | 2.29 |

The effective representation of actual loss characteristics in the presence of environment variation is validated by the strong correlation in the polynomial model. The validation shows that the shading effect, transient irradiance fluctuation and differences in equipment performance must be considered when interpreting on-site measurements. The accuracy and feasibility of the proposed power loss model in real PV plants is validated in the field measurements.

### 3.4 Discussion

The results show that both tilt angle and azimuth orientation strongly and nonlinearly affect the performance of PV systems. In the Malaysian state capitals, we observed different power-loss profiles that reflect the combined impacts of geographical location, local climate, and solar path characteristics. This finding agrees with earlier studies that noted a significant sensitivity of PV energy yield to installation geometry, especially in tropical and near-equatorial regions [4], [6], [8]. The simulation results indicate that deviations from the optimal tilt angle cause increased power losses. This effect becomes more pronounced at steeper angles beyond 35°. Similar patterns have been noted by Tamoor et al. [4] and Mamun et al. [8], who pointed out that even minor differences from the optimal tilt can lead to significant drops in annual energy output. In this study, the impact is further worsened by misalignment in azimuth. This confirms that tilt and orientation should be evaluated together instead of separately. This finding aligns with the work of Dimd et al. [7] and Oh et al. [13], who highlighted the significance of orientation-related loss behavior in rooftop and building-integrated PV systems.

The evaluation of different Malaysian sites demonstrates that a single fixed tilt azimuth configuration fails to produce accurate PV yield predictions throughout the entire country. The loss characteristics of a location depend on three main factors which include atmospheric conditions and how solar irradiance spreads across the area and the way local shading affects the environment. Research studies conducted in different locations with different climate patterns have shown similar location-based behavioral patterns [10-12]. The research findings demonstrate that the SEDA Malaysia formula along with other empirical methods fail to recognize how tilt and azimuth angles interact with each other.

The proposed polynomial power-loss model successfully models the non-linear connection between installation geometry and energy loss. The model shows strong reliability because the predicted results match the experimental data obtained from on-site validation tests. The research supports previous studies which recommend using regression-based or empirical models to enhance PV performance prediction through field data validation [11], [14]. The estimated values show minor differences with measured values because of brief changes in solar radiation and cloud presence and additional energy losses which stem from dirt accumulation and temperature changes.

The enhanced discussion shows that using location-based tilt and azimuth coefficients leads to better results in PV yield prediction accuracy. The proposed model serves as an operational design system which helps system planners and installers reduce power losses while they optimize rooftop PV arrangements based on Malaysian weather patterns.

## 4.0 CONCLUSION

This paper explored the impacts of tilt angle and azimuth orientation on the PV system performance in Malaysia, and formulated a polynomial power-loss model from extensive PVSyst simulations and regression analysis. The resulted equation has described the nonlinearity of orientation dependent power loss and was verified by on site measurements, through which the measured results show close agreement with those predicted. These results validate the accuracy of the model and its suitability for practical use, thus providing designers an effective method of estimating power losses and optimising module orientation to maximise overall energy yield. The results also emphasize the need to consider local climatic as well as geographical features in planning PV installations.

The model work well but there are several limitations were identified which is an unmodelled loss factors, environment variability and potential effect on the predictive model. The data collection to other places, include shading, temperature and module degradation as additional input parameters, and investigate more sophisticated modelling techniques must be extended for the future studies to improve equation prediction. For the national design guidelines and wider application in actual PV deployments, the more data need to be collected in the field and engagement with industry could help to improve the incorporation of the model. Finally, this study has developed an importance for future improvement in PV system configuration and contribute in more knowledge and sustainable development of solar energy in the tropical areas.

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