Optimal Orientation and Tilt Angle for Maximizing in-Plane Solar Irradiation for PV Applications in Singapore

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***Abstract*—The performance of photovoltaic (PV) modules and systems is affected by the orientation and tilt angle, as these parameters determine the amount of solar radiation received by the surface of a PV module in a specific region. In this study, three sky models (Liu and Jordan, Klucher, and Perez *et al.*) are used to estimate the tilted irradiance, which would be received by a PV module at different orientations and tilt angles from the measured global horizontal irradiance (GHI) and diffuse horizontal irradiance (DHI) in Singapore (1.37°N, 103.75°E). Modeled results are compared with measured values from irradiance sensors facing 60° NE, tilted at 10°, 20°, 30°, 40°, and vertically tilted irradiance sensors facing north, south, east, and west in Singapore. Using the Perez *et al.* model, it is found that a module facing east gives the maximum annual tilted irradiation for Singapore's climatic conditions. These findings are further validated by one-year comprehensive monitoring of four PV systems (tilted at 10° facing north, south, east, and west) deployed in Singapore. The PV system tilted 10° facing east demonstrated the highest specific yield, with the performance ratio close to those of other orientations.**

***Index Terms*—Irradiation maximization, optimal tilt angle, orientation, PV modules, solar irradiance.**

I. Introduction

Among the most important parameters that affect the performance of a photovoltaic (PV) system are the orientation and tilt angle selected for the array installation, which determines the amount of solar radiation received by the surface of the PV modules. For Singapore (1.37° N, 103.75° E), with very limited land area (country size ∼720 km^2), it is desirable that modules are oriented in such a way as to harness the maximum solar energy possible. In this paper, we study the optimal orientation and tilt angle for fixed-tilt PV systems in Singapore to maximize solar energy resource harvesting, using both modeling and experimental approaches.

In the past, many authors presented models to predict solar radiation on inclined surfaces from the typically measured global horizontal irradiance (GHI) and diffuse horizontal irradiance (DHI) [1]–[8]. While the direct beam radiation on a tilted surface can be calculated using geometric relations, the conversion for the diffuse radiation is more complex and has been approached using different models. The first-generation model converts the horizontal diffuse radiation to the tilted plane by assuming that the total sky diffuse radiation content is isotropically distributed [1]. However, this assumption is not strictly true. Newer models treat the diffuse radiation component as anisotropically distributed, where the irradiance is treated as the sum of circumsolar and background sky diffuse components [2]–[8].

For this study, three transposition models (Liu and Jordan [1], Klucher [4], and Perez *et al.* [8]) are investigated to find the best model for Singapore's climatic conditions. The accuracies of the models are determined by comparing the estimated results with measured values in the field. Comparisons are made for surfaces oriented at 60° NE with tilt angles of 10°, 20°, 30°, 40°, and vertically mounted surfaces facing north, south, east, and west. The normalized root mean square error (NRMSE) statistical method is used to quantify the accuracy of each model compared with the measured results.

Using hourly GHI and DHI data measured over a period of three years, we observe the annual irradiation variability in Singapore. We additionally use the data to calculate the hourly tilted irradiance for all possible tilt angles and orientations. The hourly tilted irradiances are then summed up in order to obtain annual tilted irradiances. The tilt angle and orientation that yield the highest annual tilted irradiance is considered to be the optimal tilt angle and orientation for the observed year. Finally, with the availability of data from a PV site, during the third year of assessment, the estimated optimal orientation is validated with a one-year evaluation of the PV systems' monitored data.

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Fig. 1. Photograph of the irradiance measurement station located on the roof of the Solar Energy Research Institute of Singapore.

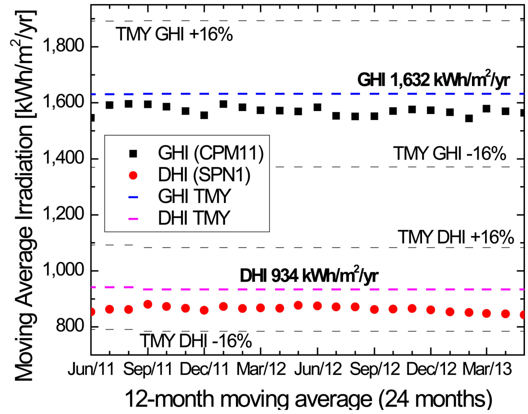

Fig. 2. Average annual GHI and DHI shown as a moving 12-month average. The TMY for Singapore as per Meteonorm 7.1 is 1 632 kWh/m^2/yr for GHI and 934 kWh/m^2/yr for DHI.

II. Irradiance Measurement Station for Model Evaluation

The irradiance measuring station (see Fig. 1) is located on the roof of the Solar Energy Research Institute of Singapore (SERIS) building at the National University of Singapore (NUS) campus (1.30° N, 103.77° E). It commenced operations in June 2010.

At its final configuration, 12 irradiance measurement sensors are installed: one silicon sensor tilted at 0° measuring GHI, four silicon sensors facing 60° NE tilted at 10°, 20°, 30°, and 40°, four silicon sensors vertically tilted facing north, south, east, and west, a pyranometer (CMP11 from Kipp and Zonen) measuring GHI, and a sunshine pyranometer (SPN1 from Delta-T) measuring both GHI and DHI.

All silicon sensors are calibrated every 2 years at Fraunhofer ISE's CalLab with ±2% accuracy, while all other sensors are calibrated at the same time interval at the respective manufacturers. The silicon sensors are crystalline silicon PV devices with temperature correction. After the station completed a 1-year period of data collection in May 2011, annual average for GHI and DHI for the following 2 years (June 2011 to May 2013) was created, by plotting a moving 12-month average of these two irradiation parameters for comparison against the long-term typical meteorological year (TMY) for Singapore as per Meteonorm 7.1 (see Fig. 2).

Although climatic conditions do vary on a yearly basis, they usually stay within a range of ±16% [9], as also shown in Fig. 2.

All sensors are installed on the rooftop without obstructions from nearby buildings, hence free from any shading throughout the year. The sensors are cleaned every week, to prevent soiling accumulation. Data sampling for all parameters takes place every 1 s, with logging at 1 min intervals.

For an initial analysis of the weather conditions in Singapore, data from the first full 12-month period (June 2010 to May 2011) for GHI and DHI are analyzed. For in depth analysis, tilted silicon sensors were installed during the second year. We average data to hourly intervals for calculation and comparison with the modeled results (second full 12-month period, from June 2011 to May 2012). Finally, with the availability of data from a real-world PV system, the third year (June 2012 to May 2013) is used for the validation of our findings.

III. Computation Methodology

Three transposition models are used to convert the hourly measured GHI and DHI into hourly tilted irradiance. The models are Liu and Jordan's isotropic diffuse sky model [1], Klucher's model [4], and Perez *et al.*'s model [8]. The Liu and Jordan model is one of the earliest and simplest models. Because of its simplicity, it is most widely used in estimating the tilted irradiance. The models from Klucher and Perez *et al.* offer better accuracy, but increase the computational intensity. The idea behind this study is to investigate models with different complexity and to benchmark their accuracy in modeling tilted irradiance for Singapore's climatic conditions.

A. Liu and Jordan Model

The Liu and Jordan model is one of the earliest and simplest irradiance models [1]. It assumes an isotropic diffuse sky model and can be computed in the following way:

$$I_T = I_b R_b + I_d \left(\frac{1+\cos\beta}{2}\right) + I\rho_g \left(\frac{1-\cos\beta}{2}\right) \quad (1)$$

where I_T is the tilted irradiance, I_b the beam irradiance on a horizontal surface, R_b the ratio of beam radiation on the tilted surface to that on a horizontal surface at any time, I_d the diffuse horizontal irradiance, β the tilt angle, I the global horizontal irradiance, and ρ_g the ground reflectance. An in-depth understanding of this model is available in the literature [1], [10], [11]. While this is the most trivial method, the assumption of an isotropic diffuse sky is not strictly true.

B. Klucher Model

The diffuse content of the sky is anisotropic in nature. There is an increase in radiation intensity around the circumsolar region of the sky and at the horizon. Temps and Coulson [3] developed an anisotropic sky model for a clear sky by modifying the isotropic model, to take into account the horizontal and circumsolar brightening

$$I_T = I_b R_b + I_d \left(\frac{1+\cos\beta}{2}\right)\left(1+\sin^3\frac{\beta}{2}\right) \times (1+\cos^2\theta\sin^3\theta_z) + I\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (2)$$

where θ is the angle of incidence and θ_z the zenith angle. $(1+\sin^3\frac{\beta}{2})$ accounts for the increase in sky light near the horizon during clear days, and $(1+\cos^2\theta\sin^3\theta_z)$ accounts for sky brightening near the sun.

In further studies, Klucher showed that the Temps and Coulson model provides an excellent prediction for clear-sky conditions, but overestimates for overcast skies. He also found the opposite to be true for the Liu and Jordan model. He then further modified the Temp and Coulson model to [4]

$$I_T = I_b R_b + I_d \left(\frac{1+\cos\beta}{2}\right)\left(1+F\sin^3\frac{\beta}{2}\right) \times (1+F\cos^2\theta\sin^3\theta_z) + I\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (3)$$

where $F = 1-\left(\frac{I_d}{I}\right)^2$ is the modulating function to correct the Temps and Coulson clear-sky anisotropic model. Under an overcast sky, F becomes zero, reducing the Klucher model to the Liu and Jordan model. Under a clear sky, F approaches 1, reducing the Klucher model to the Temp and Coulson model.

C. Perez et al. Model

The Perez *et al.* model [8] is based on a detailed statistical analysis of the sky's diffuse components. The model breaks the diffuse irradiance into three components of isotropic background, circumsolar, and horizon zone

$$I_{d,\mathrm{tilt}} = I_d\left(\frac{1+\cos\beta}{2}\right)(1-F_1) + F_1\frac{\cos\theta}{\cos\theta_z} + F_2\sin\beta \quad (4)$$

where $I_{d,\mathrm{tilt}}$ is the total tilted diffuse irradiance, F_1 the circumsolar brightness coefficient, and F_2 the horizon brightness coefficient. F_1 and F_2 are related to sky irradiance conditions, which are described using three variables: 1) sun position (zenith angle θ_z); 2) sky clearness index ε; and 3) brightness index Δ. The sky clearness index ε is defined as

$$\varepsilon = \frac{(I_d + I_{b,n})/I_d + 1.041\theta_z^3}{1+1.041\theta_z^3} \quad (5)$$

where $I_{b,n}$ is the direct normal irradiance. The sky brightness index Δ is defined as

$$\Delta = m\frac{I_d}{I_E} \quad (6)$$

where m is the air mass and I_E the extraterrestrial irradiance. For the model, ε is separated into eight bins. For different bins, the brightness coefficients F_1 and F_2 are considered linear functions of θ_z and Δ

$$F_1 = f_{11}(\varepsilon) + \Delta f_{12}(\varepsilon) + \theta_z f_{13}(\varepsilon) \quad (7)$$

$$F_2 = f_{21}(\varepsilon) + \Delta f_{22}(\varepsilon) + \theta_z f_{23}(\varepsilon) \quad (8)$$

TABLE I
PEREZ MODEL COEFFICIENTS TO DESCRIBE DIFFERENT SKY CONDITIONS [8]

ε	f_{11}	f_{12}	f_{13}	f_{21}	f_{22}	f_{23}
[1, 1065)	-0.0083	0.5877	-0.0621	-0.0596	0.0721	-0.0220
[1.065, 1.23)	0.1299	0.6826	-0.1514	-0.0189	0.066	-0.0289
[1.23, 1.5)	0.3297	0.4869	-0.2211	0.0554	-0.064	-0.0261
[1.5, 1.95)	0.5682	0.1875	-0.2951	0.1089	-0.1519	-0.0140
[1.95, 2.8)	0.8730	-0.3920	-0.3616	0.2256	-0.4620	0.0012
[2.8, 4.5)	1.1326	-1.2367	-0.4118	0.2878	-0.823	0.0559
[4.5, 6.2)	1.0602	-1.5999	-0.3589	0.2642	-1.1272	0.1311
[6.2, ∞)	0.6777	-0.3273	-0.2504	0.1561	-1.3765	0.2506

where the six coefficients f_{ij} for each category of ε are found by the least square fit to the experimental data. A recommended set of these coefficients (using experimental data from different locations and climatic conditions [8]) is given in Table I.

To find the total tilted irradiance, the beam irradiance and the ground reflectance must be added

$$I_T = I_b R_b + I_{d,\mathrm{tilt}} + I\rho_g\left(\frac{1-\cos\beta}{2}\right). \quad (9)$$

IV. RESULTS

Using the three models discussed earlier, hourly measured GHI and DHI are converted into hourly tilted irradiance for different orientations and tilt angles of interest. The modeled results are then compared with the experimental results.

A. Measurement Results

Readings from calibrated silicon irradiance sensors at various orientations and tilt angles were analyzed (over a period of one year) to provide a validation of the modeling results; they also serve as an initial indication of the optimal orientation and tilt angle for maximum energy harvesting. The annual irradiance (from the chosen 12-month period from June 2011 to May 2012) received by each silicon sensor is summarized in Table II. As can be seen, the horizontal sensor and the sensor oriented at 60° NE with a tilt angle of 10° received the highest annual irradiance. Among all the vertically tilted sensors, the east-facing sensor received the highest annual irradiation. However, since the uncertainty of the measurement (±2%) is higher than the gain/loss verified for silicon sensors from 0° to 20° tilt, it is not possible to determine the best tilt angle.

From the yearly measurements, a typical day is calculated. A typical day is obtained by averaging the yearly measurements (1-h data) into a single day. A typical day for irradiance sensors at different orientations are shown in Fig. 3. From Fig. 3, among the group of sensors oriented at 60° NE, the maximum irradiance is observed at a tilt angle of 10°. Further increasing the tilt angle leads to a decrease in irradiance capture. Also noticeable is that the east façade irradiance sensor has a much higher irradiance reception compared with the west façade sensor. This

TABLE II
ANNUAL IRRADIATION (kWh/m^2) RECEIVED BY SILICON SENSORS AT DIFFERENT ORIENTATIONS AND TILT ANGLES IN SINGAPORE FROM JUNE 2011 TO MAY 2012

Orientation, tilt angle	Annual irradiation [kWh/m^2]	Gain/loss vs. baseline [%]
-, 0° tilt	1,524	N.A. (baseline)
60° NE, 10° tilt	1,524	+0.0%
60° NE, 20° tilt	1,495	-1.9%
60° NE, 30° tilt	1,438	-5.6%
60° NE, 40° tilt	1,361	-10.7%
0° N, 90° tilt	597	-60.8%
180° S, 90° tilt	545	-64.3%
90° E, 90° tilt	784	-48.5%
270° W, 90° tilt	685	-55.0%

Baseline is the 0° tilt sensor.

can be explained by the fact that Singapore is usually sunnier in the morning compared with the afternoon, because of cumulus clouds building up in the afternoon, which is typical for tropical locations. The sensor facing north has a slightly higher irradiance reception than the sensor facing south, even though the sun path in Singapore is equally long in the south as in the north, due to the close proximity to the equator. This might be due to yearly seasonal variations.

Table II and Fig. 3 provide an early indication that PV modules/systems facing east would receive a higher amount of solar irradiance in Singapore.

B. Irradiance Model Comparison

Using the hourly measured GHI and DHI over the 1-year period, tilted irradiance values for the different orientations and tilt angles of interest are calculated. The derived irradiances using the Perez *et al.* model are compared with the measured readings and shown in Fig. 4 for 10°, 20°, 30°, and 40°, and in Fig. 5 for the façade sensors.

At lower tilt angles, the modeled results are very accurate; at higher tilt angles, the modeled values show a stronger deviation. This is due to the error of assuming a constant ground reflectance ρ_g of 0.2. At higher tilt angles, both the diffuse component and the ground reflected component of sunlight become more dominant in determining the total tilted irradiance; the small error in ρ_g is exacerbated at higher tilt angles.

For comparison of the three different models, we use the statistical NRMSE method to calculate the deviation of the modeled results from the measured results. The NRSME results for the three models are shown in Table III, for all different orientations and tilt angles.

From Table III, it can be seen that all models offer very accurate results at low tilt angles. As the angle increases, the NRMSEs also increase. Among all three models, the model from Perez *et al.* offers the most accurate results (i.e., lowest NRMSE). This is not surprising because this model consists of coefficients that are obtained empirically and statistically based

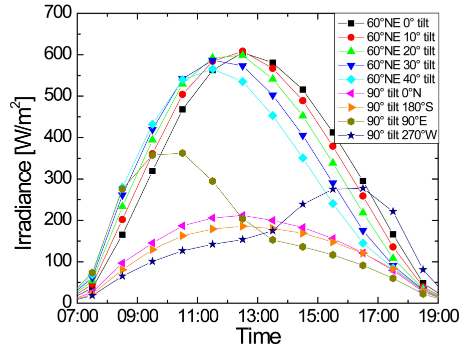

Fig. 3. Irradiance distributions for a typical day in Singapore based on empirical data from June 2011 to May 2012 for irradiance sensors facing 60° NE, tilted at 0°, 10°, 20°, 30°, and 40° and vertically mounted irradiance sensors facing north, south, east, and west (1-h data; the lines are guides to the eye).

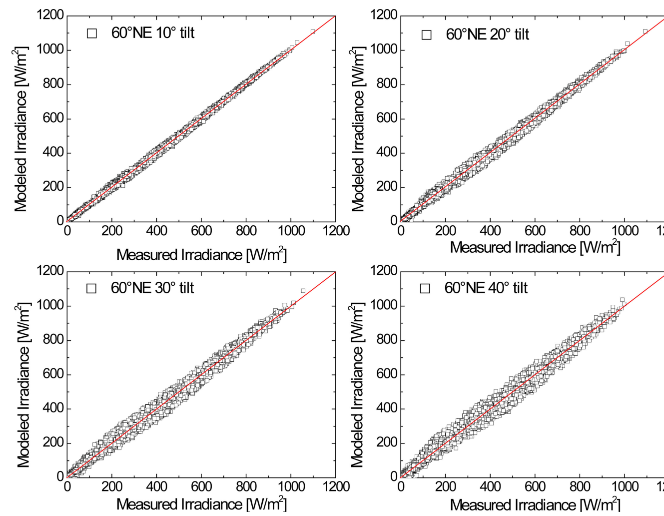

Fig. 4. Measured versus modeled irradiance using the Perez *et al*. model for irradiance sensors oriented at 60° NE with tilt angles of 10°, 20°, 30°, and 40° in Singapore. The comparison is done for the full 12-month period from June 2011 to May 2012.

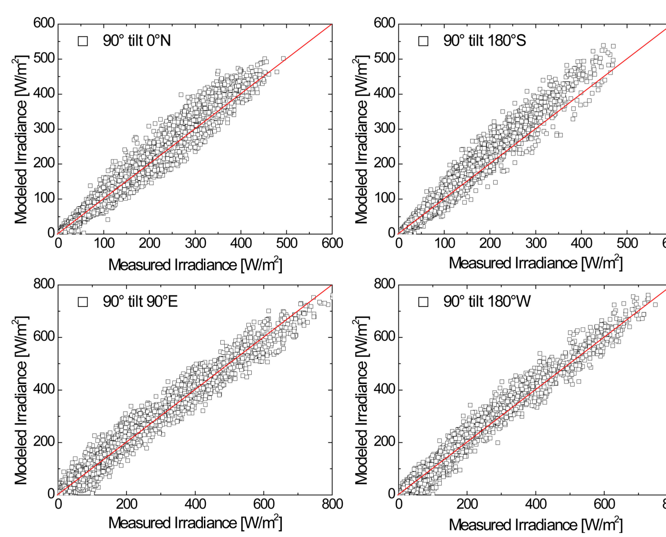

Fig. 5. Measured versus modeled irradiance using the Perez *et al*. model for vertically tilted irradiance sensors facing north, south, east, and west in Singapore. The comparison is done for the full 12-month period from June 2011 to May 2012.

TABLE III
COMPARISON OF THE NORMALIZED ROOT MEAN SQUARE ERRORS (NRMSE) FOR ALL DIFFERENT ORIENTATIONS AND TILT ANGLES AVAILABLE AT SERIS' METEOROLOGICAL STATION IN SINGAPORE FOR THE THREE TRANSPOSITION MODELS: LIU AND JORDAN, KLUCHER, PEREZ *et al.*

	NRMSE [%]							
	60°NE 10° tilt	60°NE 20° tilt	60°NE 30° tilt	60°NE 40° tilt	0°N 90° tilt	180°S 90° tilt	90°E 90° tilt	270°W 90° tilt
Liu & Jordan	1.0	1.9	2.8	3.7	6.4	7.8	5.0	5. 2
Klucher	1.2	1.6	2.3	3.0	4.5	5.3	4.3	4.1
Perez *et al.*	0.6	1.1	1.6	2.2	3.6	5.1	3.0	3.2

on different sky conditions. Since the Perez *et al.* model offers the most accurate predictions, it is used in the following to find the optimal orientation and tilt angles for PV modules in Singapore's climatic conditions.

C. Optimal Orientation and Tilt Angle for Maximum Annual Tilted Irradiation Harvesting

Using the Perez *et al.* model, the annual tilted irradiation for all possible orientations and tilt angles were calculated. Fig. 6 summarizes the results in a polar contour plot for the first year of data acquired by our station (June 2010 to May 2011). As can be seen, a surface oriented slightly south of due east and with a tilt angle of 26° would yield the maximum annual irradiation of 1 562 kWh/m^2 recorded for the evaluated year. This can be explained by the fact that Singapore is usually sunnier in the morning than in the afternoon, as mentioned earlier.

Initial findings (see Fig. 6) showed that a module tilted facing east will receive highest annual solar irradiation. However, this observation might be due to the seasonal variation for that particular year. The GHI and DHI data were measured for two more years from June 2011 to May 2012, and then from June 2012 to May 2013. The polar contour plots of the annual tilted irradiation for different tilts and orientations are shown in Figs. 7 and 8.

Both Figs. 7 and 8 show that a module facing east would have received highest annual irradiation for the two aforementioned years under evaluation. The optimal tilt angles shown in Figs. 7 and 8 are lower than the one showed in Fig. 6. While there is some seasonal variations effect, Figs. 6–8 confirm that a module facing east will receive the highest annual irradiation. In practice, PV installers might want to have more flexibility when mounting PV modules at a site, for instance, to avoid the extra cost of more complex mounting structures. For this purpose, the orientation and tilt angles which represent values that are less than the optimal point to a maximum of 5% are shown within the dotted circle lines in Figs. 6 through 8.

D. System Results

To further validate the findings in Section IV-C, several PV systems were evaluated with identical monitoring equipment. At the site under study in Singapore, four identical PV subsystems with the same installed capacity, same module, and

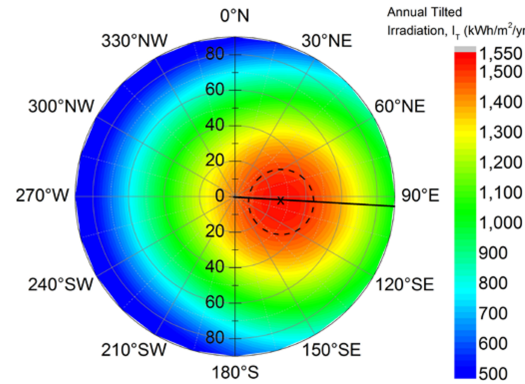

Fig. 6. Polar contour plot of annual tilted irradiation for different tilts and orientations in Singapore. The radius indicates the tilt angle, while the polar angle refers to the orientation. A surface facing 97° SE with tilt angle of around 26° receives the highest annual irradiation of 1 562 kWh/m^2, shown as the "x" in the polar contour plot, based on empirical GHI and DHI data of one-year period of June 2010 to May 2011. The orientation and tilt angles, which represent values that are less than the optimal point to a maximum of 5%, are shown within the dotted circle.

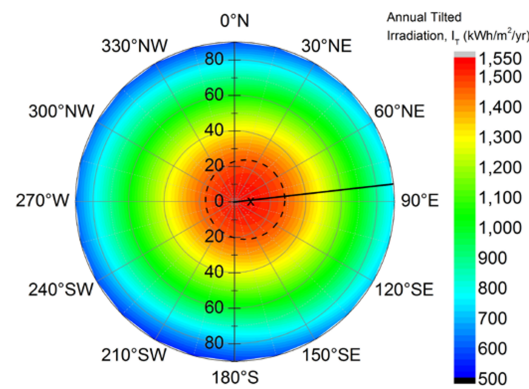

Fig. 7. Polar contour plot of annual tilted irradiation for different tilts and orientations in Singapore. The radius indicates the tilt angle, while the polar angle refers to the orientation. A surface facing 78° NE with tilt angle of around 7° receives the highest annual irradiation of 1 531 kWh/m^2, shown as the "x" in the polar contour plot, based on empirical GHI and DHI data of one-year period of June 2011 to May 2012. The orientation and tilt angles, which represent values that are less than the optimal point to a maximum of 5%, are shown within the dotted circle.

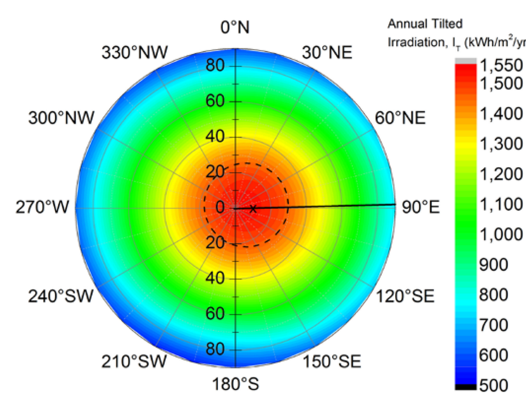

Fig. 8. Polar contour plot of annual tilted irradiation for different tilts and orientations in Singapore. The radius indicates the tilt angle, while the polar angle refers to the orientation. A surface facing 88° NE with tilt angle of around 9° receives the highest annual irradiation of 1 523 kWh/m^2, shown as the "x" in the polar contour plot, based on empirical GHI and DHI data of one-year period of June 2012 to May 2013. The orientation and tilt angles, which represent values that are less than the optimal point to a maximum of 5%, are shown within the dotted circle.

same inverter brands and specifications were analytically monitored for a period of 12 months (June 2012 to May 2013). The systems are all tilted at 10° and oriented in the four cardinal directions (one subsystem for each orientation): north (0°), south (180°), east (90°), and west (270°). In order to assess the electrical performance of each PV system, both the dc and ac outputs were monitored. For the dc output, precision shunts and transducers with small uncertainties (±0.2%), and for the ac output, class-0.5% energy meters were installed after each subsystem's inverter outputs. The calculation of the performance ratio (PR) of each PV system is based on the readings of four in-plane silicon sensors (one per subsystem). Similar to the SERIS meteorological station (see Fig. 1), these silicon sensors were also calibrated at Fraunhofer ISE's CalLab with ±2% accuracy.

Fig. 9 shows the monthly irradiation variations for each of the orientations. The east-oriented silicon sensor (1 457 kWh/m^2 total annual irradiation for the measured period) received +4.1% more irradiation than the west-oriented sensor (1 399 kWh/m^2). The difference between the north facing and south facing sensors was negligible. Overall, the highest annual irradiation occurred for the east orientation, which was 1.0% higher than the second-best orientation (south) and 4.1% higher than the worst orientation (west). While the 1% difference between east and south sensors fall within the 2% uncertainty of the measurements, it is clear that the east facing sensor has an advantage over the west facing sensor.

For each PV system, the data are only collected when the site's global irradiance (GHI) is above 50 W/m^2. This threshold was set to arbitrarily create a filter level which would guarantee that all four PV systems are concurrently operational at any given point-in-time, as well as filtering out nonmeaningful data around the inverter cut-off point. The overall availability of the monitoring system was very high, with only about 0.1% of data points lost in over half a million points for the analyzed period.

As shown in Table IV, and as expected from Section IV-A, an east-oriented PV system will have a higher yield in Singapore compared with other azimuths. In the investigated 12-month period, the east-facing system generated 2% more electricity than the west-facing system. Relating the annual yield to the in-plane irradiation, which is expressed in the performance ratio, there was no statistically significant variation between the four investigated systems (note that the measurement error is in the order of ±3% [12], [13]). However, the west-facing system might have a slightly better PR value; this could be due to the slightly lower module temperatures (∼0.6 °C) recorded for this system as compared with the east-facing system. As module temperatures account for 45%–60% of all losses associated with PV systems in the tropics [12], even variations in the order of a few °C can significantly affect a system's PR.

Climatic conditions do vary on a yearly basis, but these are usually constrained to ranges within ±16% from TMYs. While the results shown in Figs. 7–9 are empirically drawn from different calendar years at the SERIS meteorological station, it could be demonstrated that similar patterns of higher irradiation on east-oriented surfaces are present.

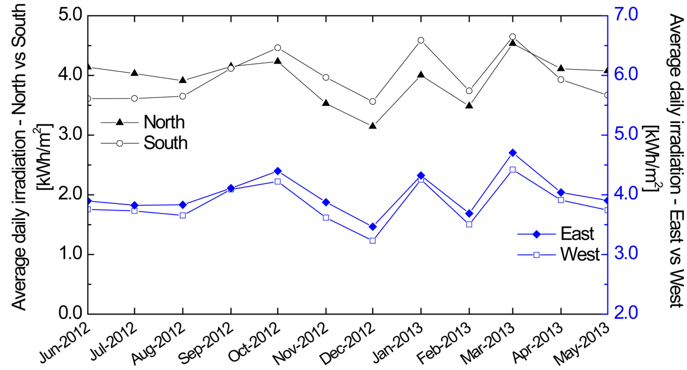

Fig. 9. Monthly irradiation variations (shown as daily averages). The two y-axes have been offset to facilitate viewing. The lines are guides to the eye.

TABLE IV
PERFORMANCE PARAMETERS OF THE FOUR INVESTIGATED PV SYSTEMS

	PV (north)	**PV (south)**	**PV (east)**	**PV (west)**
ΣE_{ac}, with $G_{mod} > 50$ W/m^2 [kWh]	12,237	12,225	12,360	12,147
Annual irradiation [kWh m^{-2} yr^{-1}], Fig. 9	1,436	1,442	1,457	1,399
PV system specific yield [kWh kW$_p^{-1}$ yr^{-1}]	1,239	1,238	1,252	1,230
Performance ratio [%]	86.9	86.4	86.2	87.7
Average T_{mod}, with $G_{mod} > 50$ W/m^2 [ºC]	38.8	38.9	39.7	39.1

Data logger availability was 99.9% for all four systems.

V. CONCLUSION

Using hourly measured global horizontal irradiance (GHI) and diffuse horizontal irradiance (DHI) data, modeling was performed to calculate the hourly tilted irradiance for different orientations and tilt angles in Singapore. The optimal orientation and tilt angles were then determined by finding the value for which the total radiation on a particular PV surface was the highest for the three-year period under investigation (June 2010 to May 2013). For this study, the sensors at the meteorological station were cleaned every week, to prevent soiling. For a future study, the investigation of the soiling effect on the PV performance of different module orientations will also be taken into consideration. The modeling results were validated by irradiance sensors and measurements on a real-world PV system.

Using the Perez *et al.* model, it was found that surfaces tilted eastward yield maximum annual in-plane irradiation in Singapore climatic conditions. PV systems at different orientation, but identical tilt and system configurations, were evaluated, with an east-oriented system showing the highest yield. These findings provide useful information for PV system integrators, both in Singapore and in equatorial countries with similar climatic conditions, on how to best design PV systems for maximized energy yield.

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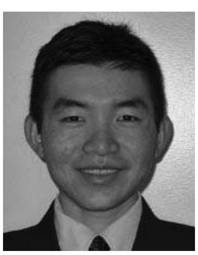

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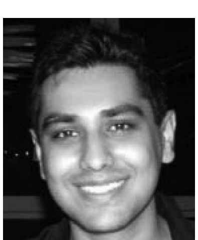

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