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ORIGINAL RESEARCH PAPER

A Study on Implementation of PV Tracking for Sites Proximate and Away from the Equator

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Abstract

The performance of photovoltaic (PV) system depends upon the orientation and the site climatic conditions. Solar PV tracking systems align the modules perpendicular to the incoming solar radiation. In this paper, six locations with latitudes 0° through 55° were selected to investigate the PV system performance using single-axis (horizontal and vertical) and two-axis tracking systems compared to the fixed south-oriented PV system. It was found that single-axis (vertical axis) tracker optimally tilted is the most promising for sites near the equator and achieves around 19% more energy output over the fixed south-oriented solar panel system. Moreover, it is considered simpler compared to the two-axis tracking system. It is true that the two-axis tracking system could harvest around 4% more energy than the vertical axis tracker optimally tilted system for sites near and far from the equator. However, such increase in energy may not sound feasible as the two-axis system is consuming more power for tracking and considered more complicated compared to the vertical axis tracking system. The novelty of this work is that, it introduces a new concept for the optimum tilt for the single-axis (vertical axis) tracking system.

Keywords Photovoltaic (PV) · Fixed south-oriented · Tilt angle · Tracking system · Vertical axis tracker optimum tilt

Introduction

Amongst the available renewable energy resources, solar energy is the most abundant. The total incoming solar radiation that reaches the surface of the earth is divided into beam radiation and diffuse radiation. For locations further away from the equator, the components of global radiation components would have a different effect. The beam radiation received would be lower than locations near the equator and this would cause a difference in ambient temperature (Siraki and Pillay 2012). The performance of a photovoltaic (PV) module decreases as the ambient temperature increases. When the level of radiation received by PV is kept constant, a rise in temperature decreases the voltage output of the PV module. Under different levels of temperature and radiation, the performance of a PV module varies (Duffie and Beckman 2013).

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In general, the output of a PV installation is largely dependent upon the weather conditions, orientation, and the latitude of the location (Chang 2010).

Usually, PV modules are mounted using a fixed tilt installation structure, which keeps the tilt and azimuth angles unaltered. However, for fixed south-oriented installation, the PV module would be receiving mostly indirect solar irradiation, thus lowering the performance (Heslop and MacGill 2014). To compensate for this, solar panels are commonly oriented towards the equator to maximize the incoming absorption of solar radiation. Despite this, there are fluctuations ranging from diurnal, monthly, seasonal, and yearly solar radiation, deeming the performance to be site-specific (Yadav and Chandel 2013). In this study, the yearly optimum tilt angle for a fixed south-oriented PV system is considered.

A PV tracker is a device that maintains the surface of a PV module perpendicular to the incoming solar radiation to improve the energy harvested. The solar tracking system is divided into two different types, one axis (single axis) and two axes (double axis) based on their rotational axis (Mousazadeh et al. 2009). The two-axis PV tracker can be characterized into two different types, polar (equatorial) and azimuth/elevation (altitude-azimuth) tracking systems (Mondol et al. 2007).

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Table 1 Comparison of optimum tilt angle for fixed orientation panel from previous research

Location	Latitude	Methodology/apparatus	Optimum fixed tilt	Ref.
Taiwan	≈ 23.5°	PSO-NTVE, experimental	15–19°	Chang (2010)
Cairo, Egypt	30°	Fortran, TRNSYS	20–30°	Hussein et al. (2004)
Ontario, Canada	44–45°	ESP-r	32–38°	Rowlands et al. (2011)
Belgrade, Serbia	44°	Simulation	≈ 40°	Despotovic and Nedic (2015)
Northern Ireland, UK	55°	TRNSYS	30°	Rowlands et al. (2011)

Solar PV tracking systems could further be categorized based on their tracking mechanism. The passive tracking system is centered on thermal expansion of matter. When the temperature increases, the matter would experience thermal expansion. This allows actuators to move the PV module. Active trackers are more advanced as they may be using a microprocessor and optical sensors and time and date memory. It may also be auxiliary bifacial solar cell based and the mixture of the three types mentioned before.

In general, it is suggested that the optimum tilt angle of a solar panel is equal to the latitude of the location (Mondol et al. 2007). The implementation of a tracking system would increase the production of a PV module to a certain extent. Various researches had been done to determine the benefits of tracking system over the fixed south-oriented PV system as well as the optimum tilt angle and orientation for different climatic conditions at varying latitude.

In 2004, a team from the Department of Solar Energy of National Research Centre in Egypt came with a study indicating that, the most optimum tilt angle for Cairo being in the range of 20–30° facing south employing TRNSYS© software (Hussein et al. 2004).

In 2006, researchers in the UK validated the optimum tilt angle at different time frames utilizing the simulation package TRNSYS. The site selected was Northern Ireland (latitude 55°). The study established that the yearly most optimum tilt angle for fixed south-oriented PV installation is 30° facing southward (Mondol et al. 2007).

Chang (2010) investigated the optimum tilt for seven different cities in Taiwan around the latitude of 23.5°. The results indicate that the most optimum PV fixed tilt angle varies between 15 and 19° for the different locations chosen. Therefore, this prompts that the general rule of optimally tilting the modules due south at a tilt angle equal to the latitude depends on the climatic conditions of the sites (Chang 2010).

Rowlands et al. (2011) carried out a simulation based on two different locations in Ontario, Canada, at latitudes 44° for Toronto and 45° for Ottawa. The annual optimum tilt angles are found to be in the range of 32–35° and 36–38° for Toronto and Ottawa respectively (Rowlands et al. 2011).

A simulation was carried out by Despotovic and Nedic (2015), to define the most optimum tilt angle of fixed PV mounted systems at different time variations in Belgrade at latitude 44°. They concluded that, for yearly variation, the most optimum tilt angle is 39.9° (Despotovic and Nedic 2015). Table 1 illustrates a comparison of optimum tilt for a fixed orientation from a previous research.

The National Renewable Energy Laboratory (NREL) reported that for a typical installation of fixed mounted PV system tilted at 25° in contiguous USA, there is an increase of the energy gain of 3% when the tilt angle is adjusted to the optimal tilt of 20°. However, when implementing single-axis trackers, the gain ranges by 4–13%, and for a horizontal one-axis tracking system, the energy output was 12–25% compared to the fixed optimal tilt of 20°. At the same time with the two-axis tracking system the energy gain was reported as 30–45% in comparison to the fixed mounted panel (Drury et al. 2014).

An experiment was conducted in Spain to observe the difference of energy output between fixed, one-axis tracking, and two-axis tracking systems. The single-axis tracking system achieved a

Table 2 Selected locations with meteorological data

Country	City	Latitude (°)	Altitude (m)	Direct radiation (kWh/m^2/year)	Diffuse radiation (kWh/m^2/year)	Annual average temperature (°C)	Annual average wind velocity (m/s)
Singapore	Singapore	1.37	31	710.8	923.2	28.2	2.4
Malaysia	Kuala Lumpur	3.12	19	656.7	940.6	27.6	1.7
India	Ahmedabad	23.07	58	1174.0	773.0	27.2	2.2
USA	Los Angeles	33.93	35	1171.0	652.8	16.8	3.2
Italy	Bologna	44.53	36	703.0	669.4	14.2	2.6
Germany	Berlin	52.52	36	478.2	565.1	10.3	4.1

Table 3 Selected PV module specification (Quartech CS6P-250)

Technology/cell type	Poly-crystalline
Nominal power at STC	250 W
Power tolerance 0~+ 5 W	0~+ 5 W
Short-circuit current (I_{sc})	8.87 A
Opt. operating current (I_{mp})	8.30 A
Open circuit voltage (V_{oc})	37.2 V
Opt. operating voltage (V_{mp})	30.1 V
Temperature coefficient (P_{max})	− 0.43%/°C
Module area	1.609 m^2
Cell area	1.46 m^2
Module efficiency	15.54%

gain of 22.3% over the fixed mounted system whereas the two-axis tracking system obtained 2.9% increment over the single-axis tracking system (Gómez-Gil et al. 2012). Another experiment was conducted in Turkey indicating that the two-axis tracking system would yield 13.25% higher energy on average than the fixed system (Şenpinar and Cebeci 2012; Lee and Rahim 2013).

A study was conducted in 2015 to determine whether the implementation of a tracking system would be suitable in all climatic conditions. It was proved that overheating issues due to constant exposure to the sunlight would reduce the performance of the photovoltaic system. The gain of electricity in a city like Berlin (Germany) for solar tracking system was 39% higher than the fixed mounted system, whereas the gain in energy is less than 8% in Aswan, Egypt, where the ambient temperature is high (Eldin et al. 2016).

Solar panel installation at countries located at high latitudes would have a different performance variation compared to countries at the equatorial line. In 2013, a review paper proposes different models to calculate the optimum tilt for different locations. It shows that for Malaysia, the optimum tilt angle for fixed installation is almost similar to the latitude (Yadav and Chandel 2013). A study done by the University of Malaysia Pahang for the comparison of single-axis tracking with fixed mounted installation in East Coast Malaysia concluded that at noontime, both the electricity production were almost the same (Mahendran et al. 2013).

Several studies investigate the optimum orientation of fixed tilt PV systems. The results indicate that the tilt angle is closer to the latitude for locations near the equator. However, the gain from PV tracking system seems lower. Therefore, the main question to be answered is whether it is worthy to use PV tracking systems for locations near the equator such as Malaysia. Therefore, this work investigates the performance of the PV system using three different tracking systems compared to the fixed south-oriented PV system for different locations near and away from the equator. The three different tracking systems include a single-axis tracking system (horizontal axis east-west PV tracker) single-axis PV tracker (vertical axis PV tracker), and the two-axis PV tracker. The novelty of this work is that it comes with a new concept for the optimum tilt for the single-axis (vertical axis) tracking system.

Methodology

Site Selection and System Parameters

The selection criteria used for this study is to identify locations whereby the altitude is less than 100 m above sea level, to minimize the possibility of a cooling effect. There were 16 locations chosen to range in latitude from − 55° through 55°. In this paper, two locations at or near the equator, two locations further away from the equator, and two locations in between are considered. Table 1 shows the locations selected indicate the site details and their annual meteorological data.

The meteorological data is obtained by using[1] Meteonorm 7.1, which has 8325 meteorological stations across the world. For locations not covered by the meteorological stations, satellite measurement is used to compensate, thus allowing Meteonorm to generate meteorological data for any locations in the world by interpolation techniques between three of the closest stations to the specified location. The monthly irradiation values are averaged throughout 20 years whereas the temperature and wind speed are generated based on a 10-year period. Table 2 shows the selection of the location together with the annual meteorological data.

It can be seen from Table 2 that locations near and further away from the equator would receive lower global irradiation, whereas locations in between would receive a higher proportion of direct irradiation due to the difference in climatic conditions. The average yearly ambient temperature for locations away would also be lower than sites near the equator.

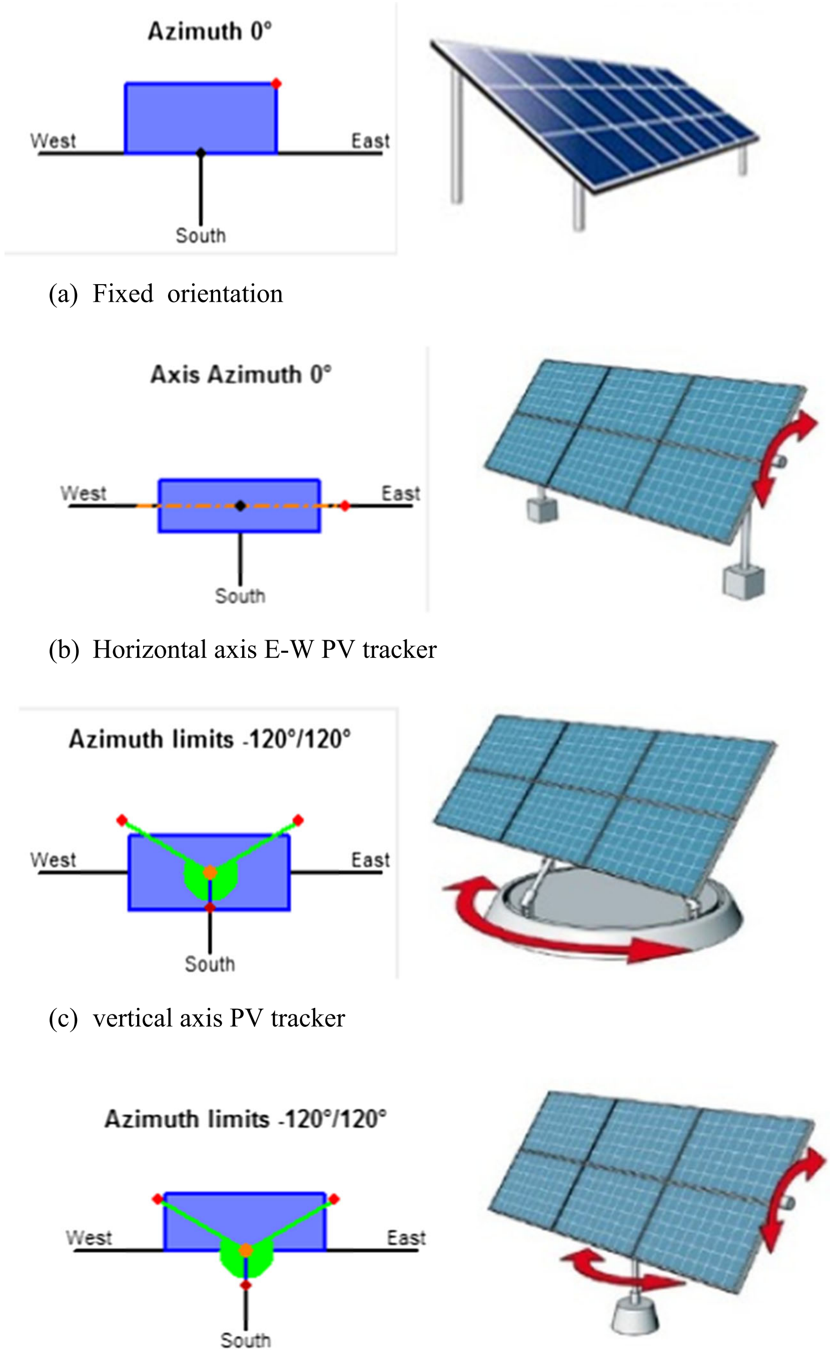
System Parameters

The selection of the photovoltaic module and inverter are based on technology and commercial availability. The selection choice for the PV module is based on its maturity, commercial availability, performance, and reliability (Makrides et al. 2012). Multi-crystalline silicone modules are known to last over 20 years with a typical cell efficiency of around 15%. The average yearly degradation of the PV module is 0.7% (Jordan and Kurtz 2013). The selected PV module is shown in Table 3.

Energy Yield Simulation

For the estimation of energy yield from the PV systems, the simulation software package[2] PVSyst 6.44© was used. The software is able to simulate different orientations with high

[1] Meteonorm 7.1© software 2016.
[2] PVSyst 6.44© software



(a) Fixed orientation

(b) Horizontal axis E-W PV tracker

(c) vertical axis PV tracker

(d) Two-axis PV tracker

Fig. 1 Illustration of the PV tracker. **a** Fixed mounted orientation, **b** single-axis, horizontal axis E-W PV tracker, **c**) single-axis vertical axis PV tracker, and **d** two-axis PV tracker (PVSyst 6.44© software) Axis (2010)

levels of flexibility. Additionally, PVSyst allows the user to customize the losses associated with the PV system design.

PV System Orientation

In this study, fixed tilt orientation, horizontal axis E-W tracker (tilt tracker), vertical axis tracker (azimuth tracker), and two-axis tracker are all illustrated in Fig. 1.

The selection of the photovoltaic module and inverter is based on the technology, maturity, performance, and reliability (Makrides et al. 2012). Multi-crystalline silicon modules are known for the last two decades with a typical cell efficiency of around 15%. The average yearly degradation of the PV module is 0.7% (Jordan and Kurtz 2013). The selected PV module is a Solar CS6P-250P. Similarly, the inverter chosen has maximum

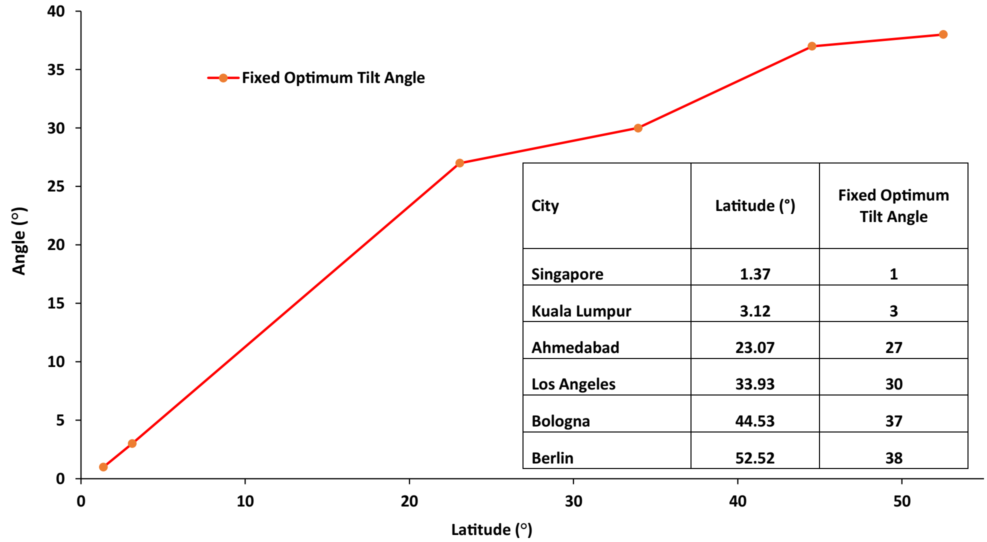


Fig. 2 Fixed south-oriented installation PV optimum tilt angle

power point tracking (MPPT), which could achieve efficiency of over 90% (Rezk and Eltamaly 2015). The system capacity used for the simulation was 5000 Wp. This system is comprised of 20 solar modules (Quartech CS6P-250), connected to SMA Sunny Boy 5000 TL-21 inverter. The simulation was performed for the different locations with different orientations while maintaining the same PV system design parameters. The major system loss occurs due to the conversion efficiency of a PV module. However, there are losses due to operating conditions away from the standard test conditions, and other losses in cables and inverter. It is reported that the energy consumption by the tracker components ranges from 2 to 3% of the energy gain (Mousazadeh et al. 2009).

Results and Discussion

PV Optimum Tilt Angle for Fixed Installation

The simulation results confirm that the optimum tilt angle for fixed installation, in the locations near the equator (Singapore and Kuala Lumpur), is equal to the latitude, while for Ahmedabad, the optimum fixed tilt angle is 27°, which is 4° higher than the latitude. However, for locations further away (Los Angeles, Bologna, and Berlin), the optimum tilt angle is lower than the latitude. The difference in optimum tilt angle for Bologna and Berlin is just 1°, even though the latitude differs by 8° (Fig. 2). This can be explained by global differential heating and air clearness indexes (Siraki and Pillay 2012; Duffie and Beckman 2013).

Fig. 3 Annual energy injected into the grid using different tracking systems at different locations

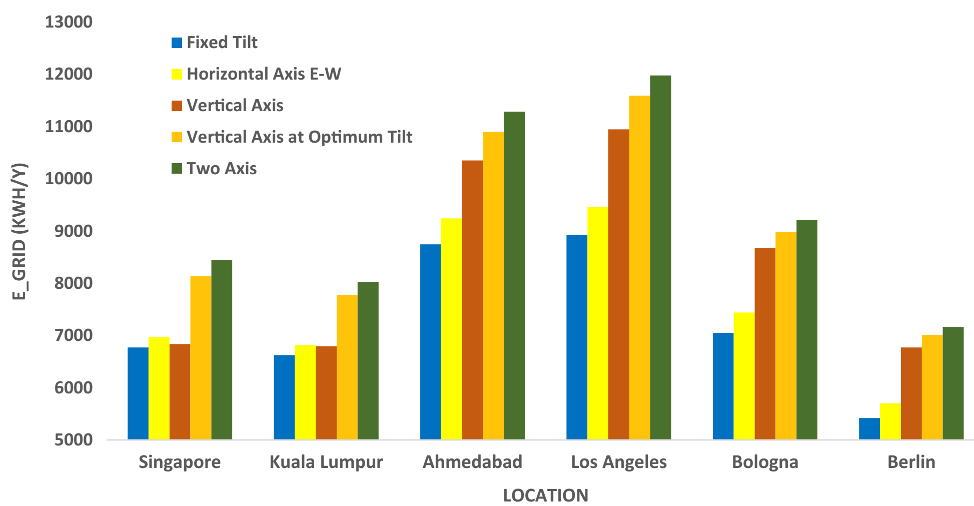


Table 4 Energy gain from single horizontal axis and vertical axis PV tracker compared to the fixed tilt installation

City	Latitude (°)	Fixed optimum tilt (°)	Fixed tilt installation (kWh/year)	H. axis (kWh/year)	H. axis over fixed tilt (%)	V. axis (kWh/year)	V. axis over fixed tilt (%)
Singapore	1.37	1	6769	6966	2.9	6835	1.0
Kuala Lumpur	3.12	3	6623	6814	2.9	6793	2.6
Ahmedabad	23.07	27	8743	9241	5.7	10,350	18.4
Los Angeles	33.93	30	8924	9462	6.0	10,947	22.7
Bologna	44.53	37	7049	7440	5.5	8677	23.1
Berlin	52.52	38	5420	5703	5.2	6771	24.9

The effect of higher diffuse radiation component would lower the optimum tilt angle for a fixed installation PV system. It was found that the maximum incident of diffuse radiation occurs on a horizontal plane. The sky clearness index also affects the optimal tilt angle for these locations. The optimal tilt angle of a collector reduces when the air clearness index increases (Chang 2009). However, the air clearness index is site-specific and changes from one location to another. Consequently, this explains the reason why the optimum fixed tilt angle for locations with higher diffuse radiation proportion is lower than the latitude.

PV Tracking System Energy Gain

The application of PV tracking system would act to adjust for the optimum orientation of the PV module to ensure higher energy gain (Mousazadeh et al. 2009). Figure 3 illustrates the annual energy injected to the grid (kWh/y) by the 5 kWp PV system, using different tracking systems at the different locations. It is clear that the horizontal axis and vertical axis trackers are not effective for the locations near the equator (Kuala Lumpur and Singapore). However, for the locations far away from the equator, the fixed tilt installation, and horizontal axis tracker are ineffective.

Table 4 illustrates the energy gain injected to the grid using horizontal axis and vertical axis PV tracker system compared to the fixed tilt installation. It is clear that the horizontal axis and vertical axis tracking system energy gain is around 3% over the fixed tilt orientation for the location near the equator. The energy gain from the vertical axis tracking system is affected by the tilt angle used. Therefore, using the optimum tilt for fixed orientation makes the system fail in the location near the equator, but shows a maximum energy gain of 24.9%, in locations far from the equator.

The vertical axis PV tracking system performance was investigated using different tilt angles. It was found that by adjusting the tilt angle of the vertical axis tracker would lead to an increase of the energy gain.

In this work, an optimum tilt angle for vertical axis trackers was studied for locations near and far from the

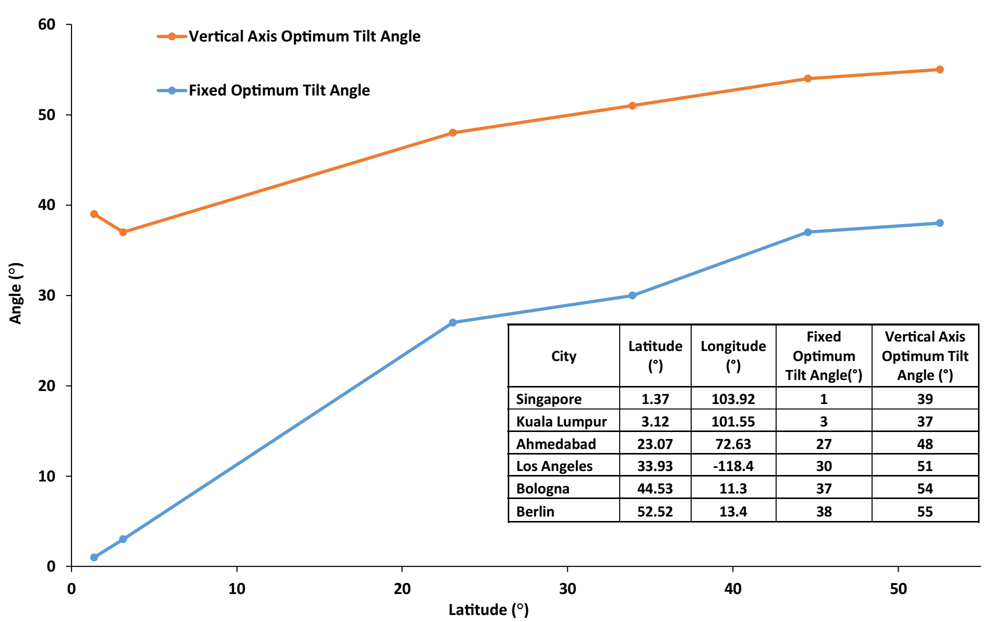


Fig. 4 The single vertical axis PV tracker optimum tilt angle compared to fixed orientation optimum tilt

equator. It is found that the vertical axis optimum tilt is much higher than the latitude for a location near the equator. Figure 4 illustrates the vertical axis optimum tilt angle compared to the fixed orientation tilt for the location near and far from the equator. The optimum tilt angle for vertical axis tracker has the highest deviation for locations near the equator (Singapore and Kuala Lumpur). While almost identical to the site latitude for the furthest selected location (Berlin).This is unlike the fixed orientation optimum tilt angle, which is generally equal to the latitude angle of the site. Thus, the optimum tilt angle for vertical axis (azimuth tracker) system is much higher than the latitude as the location is closer to the equator, implying opposite result to the optimum tilt angle for fixed tilt installation.

The two-axis tracker will adjust the tilt and azimuth angles of the PV module, such that, the incoming solar radiation almost perpendicular to the PV module surface to assure high energy gain. Table 5 compares the energy gain from two-axis tracker compared to the optimally tilted vertical axis tracker. It is clear that the two-axis tracker could harvest energy around 3% more than optimally tilted vertical axis tracker, which may not give more privilege of the two-axis tracker over the optimally tilted vertical axis tracker. The two axes are considered costlier and consume more power for the tracking mechanism. Moreover, the optimally tilted vertical axis PV tracking system is simpler and more relevant for all locations and could harvest around 24% energy gain over that gain by a fixed orientation PV system.

Conclusions

This paper investigates the performance of the PV system using three different tracking systems compared to the fixed south-oriented PV system for different locations near and away from the equator. The three different tracking systems include single-axis tracking system (horizontal axis east-west PV tracker), the single-axis (vertical axis PV tracker) tracker, and the two-axis PV tracker. The study confirmed that the optimum tilt angle for a fixed south-oriented PV system is almost equal to the latitude of the site for locations near the equator, such as in Singapore and Malaysia. While it is noticed that for the locations away from the equator the optimum tilt angle decreases with the increase of the latitude of the site.

Results reveal that it is not worthy to implement a PV tracking (horizontal axis and vertical axis) systems in locations near the equator. This is because the gain in energy is limited to 2.6–2.9%, while vertical axis can achieve more gain in a location away from the equator, compared to the horizontal axis.

The novelty in this work introduces the concept of optimum tilt for the single-axis (vertical axis) tracking system, which is different from the optimum tilt for a fixed south-oriented PV system. Figure 4 illustrates the single-axis (vertical axis tracker) tilt angle which is much higher than the latitude. Implementing the optimum tilt for the single-axis (vertical axis) tracking system lead to maximize the gain of energy from the vertical axis PV tracking system. The minimum tilt angle for Singapore and Malaysia is 37°, whereas, for locations further away such as Bologna and Berlin, the tilt angles are 54° and 55° respectively. This is due to the effect of lower solar elevation in locations away from the equator. The optimally tilted vertical axis PV tracker in Kuala Lumpur achieves an additional of 17.4%, but for Los Angeles, the gain is much higher at 29.9% over fixed tilt. The highest energy gain could be harvested from the two-axis tracking system in the range of 21 to 32% compared to the fixed south-oriented tilt for the locations studied. However, the vertical axis PV tracker, when oriented with an optimum tilt, could achieve an energy gain of 20 to 30% compared to the fixed south-oriented tilt for the locations studied.

It is true that the two-axis tracking system could harvest around 4% more energy than the vertical axis tracker. However, such increase in energy may not sound feasible as the two-axis system is consuming more power for tracking and is considered more complicated compared to the single-axis (vertical axis) tracking system.

Table 5 Energy gain from the vertical axis at optimum compared to the two-axis PV tracking system

City	Fixed opt. tilt angle (°)	Fixed tilt (kWh/year)	V. axis opt. tilt angle (°)	V. axis at opt. tilt (kWh/year)	V. axis at opt. tilt gain over fixed tilt (%)	Two axes (kWh/year)	Two-axis gain over fixed tilt (%)	Two-axis gain over the vertical axis (%)
Singapore	1	6769	39	8134	20.2	8440	24.7	3.8
Kuala Lumpur	3	6623	37	7776	17.4	8025	21.2	3.2
Ahmedabad	27	8743	48	10,897	24.6	11,281	29.0	3.5
Los Angeles	30	8924	51	11,590	29.9	11,977	34.2	3.3
Bologna	37	7049	54	8979	27.4	9211	30.7	2.6
Berlin	38	5420	55	7013	29.4	7162	32.1	2.1

This study will work as a guideline for engineers and PV system installers to optimize the yield from a chosen site. Since the data used in this work are real-time data, the error is more likely to be low, which could be proven with an experimental study as planned in the near future. Due to the abovementioned reasons, this work stands out from the contemporary works on the same topic.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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