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Optimum location and influence of tilt angle on performance of solar PV panels

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Abstract

With the growing demand of economically feasible, clean, and renewable energy, the use of solar photovoltaic (PV) systems is increasing. The PV panel performance to generate electrical energy depends on many factors among which tilt angle is also a crucial one. Among hundreds of research work performed pertinent to solar PV panels performance, this work critically reviews the role of tilt angles and particularly locating the optimum tilt angle using different methods. The past data collected for analysis can be categorized mainly into mathematical model based, experimental based, simulation based, or combination of any of these. Single-axis tracking, dual-axis tracking, simple glass cover, hydrophobic glass cover, soiled glass, clean glass, partial shadow, use of phase-change material, computational fluid dynamic analysis, etc., are the novel methods found in the literature for analysis and locating the optimum tilt angle. For illustration purpose, few figures are provided in which the optimum tilt angle obtained on monthly, seasonally, and annual basis is shown. Research works are growing in the field of computations and simulations using online software and codes. Pure mathematical-based calculations are also reported but the trend is to combine this method with the simulation method. As the PV panel performance is found to be affected by number of parameters, their consideration in any single study is not reported. In future, work is required to carry out the experiment or simulation considering the effect of soiling, glass material, temperature, and surrounding ambience on the location of optimum tilt angle. As a whole, the optimum tilt angles reported for locations exactly on the equator line, i.e., 0° latitude, ranges between − 2.5° and 2.5°, for locations just above the equator line, i.e., latitude 2.6°–30° N ranges between 5° and 28°, for 40°–70° N, it is 29°–40°, and for 71°–90° N, it is 41°–45°. For locations at 2.6°–30° S, optimum tilt angles range between − 4° and − 32°, 30°–46° S, it is − 33° to − 36°, 47°–65° S, it is − 34° to − 50°, and for 66°–90° S it is − 51° to − 62°.

Keywords Tilt angle · PV panels · Optimization · Azimuth angle · Energy output · Solar radiation

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Introduction

In the present era, providing clean and inexhaustible energy is one of the most intimidating challenges faced by human kind [1–3]. In this aspect, the solar energy provided by sun exceeds the energy required by the world. Utilizing just 10% of solar energy available on land avoids the fossil fuel necessity for power generation by twice [4–8]. In this regard, the photovoltaic (PV) panels convert the solar radiation on earth to direct electrical energy. The PV solar module is rated by peak watt (W_p) under standard solar conditions [9–15]. The solar energy transformed to the solar PV panels majorly depends on its surface tilt angles relative to the horizontal plane and the PV modules orientation azimuth angle (γ). The azimuth angle gives the position of earth with respect to north–south axis. The other solar radiation-related angles need to be understood for finding optimum tilt angles of the PV panel in order to obtain maximum output [16–21]. The azimuth and tilt angle effect the solar PV panel on their peak power production, economic value, total energy production, rate structures, electricity market prices, etc. The Zenith angle (θ) is the angle between a vertical line on earth's surface and the sun. The angle θ is calculated using Eq. 1 [21]:

$$\cos\theta = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega \tag{1}$$

where ω in local solar time is the hour angle, δ being the solar declination angle which is angle between the line from the center of sun joining the earth and respective projection on equatorial plane. φ is the location latitude, which is the angle made between radial line joining the location to the midpoint of earth with the projection of line on equatorial plane. These angles are schematically represented in Fig. 1. The other angles shown in Fig. 1 include α (solar altitude angle) which is vertical angle between sun rays projection on horizontal plane and sun rays direction passing through the point. β is the tilt angle of the PV panel with the horizontal plane [27–33].

More importantly, the solar energy converted into electrical energy with the use of PV panel depends upon amount of solar energy captured. Therefore, it is of prime importance to understand the relation between the sun and the tilt angle of PV panel at which the power output is the highest by capturing maximum solar energy [34–39]. Various algorithms/schemes are designed to optimize the tilt angles for different latitudes, time durations, local positions, regions, etc. Solar tracking is also adopted to track the trajectory of sun throughout the year or any particular season. Solar tracking system is better suited for applications which require higher efficiency like in industrial, commercial, official use, etc. In either case of finding optimal tilt angles using either manual methods or solar tracking methods, use of mathematical models is majorly reported [40–47]. Experimental methods, computational methods, and combination of these methods for finding the optimal tilt angles are also found. Presently, use of commercial software for computational fluid dynamics analysis of PV panel's thermal performance for different tilt angles is also seen. Moreover, researchers are concentrating to improve the ability of PV panels by adopting innovative methods. More recently, different mechanisms like use of nanofluids ([22–26]), phase-change materials (PCM), two-sided panes, etc., are adopted to find their effect and increase in performance of solar PV panel [48–50]. With this motivation, this article in-depth reviews the research work reported in the literature with prime focus on effect of tilt angles and estimation of optimum tilt angles on performance of PV panels analyzed using different techniques. This article focuses on tilt angle effects and optimal tilt angles of PV panels belonging to mathematical, computational, experimental, and combined approaches. In the previous review, articles on PV panels focus were made on temperature and other ambient conditions without paying attention to approach of study. Hence, these articles bring

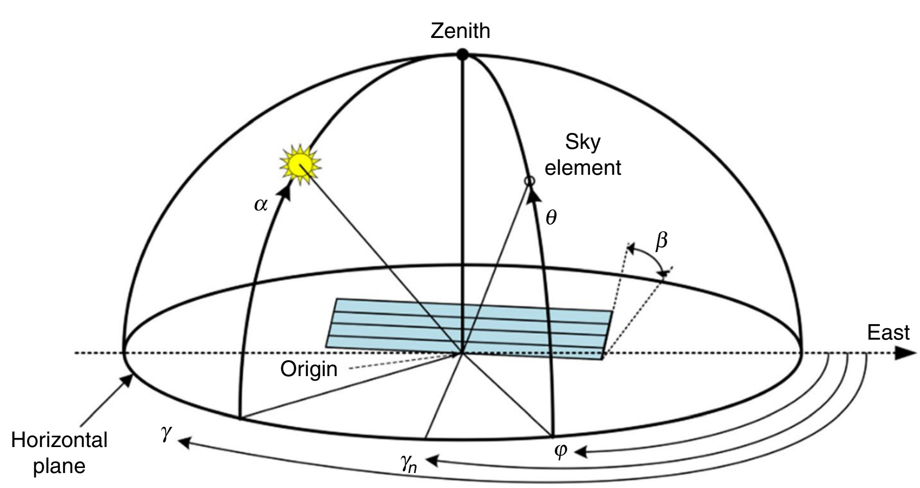


Fig. 1 Representation of different solar angles

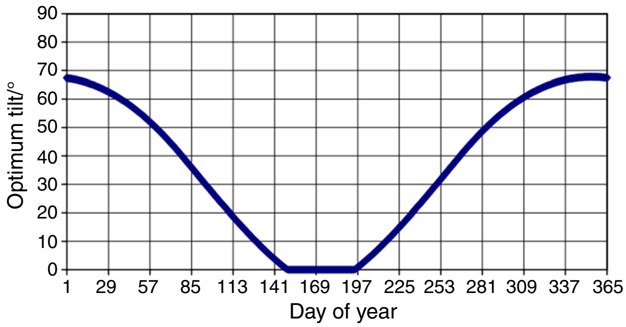


Fig. 2 Optimal tilt angles variation during every day of the year [61]

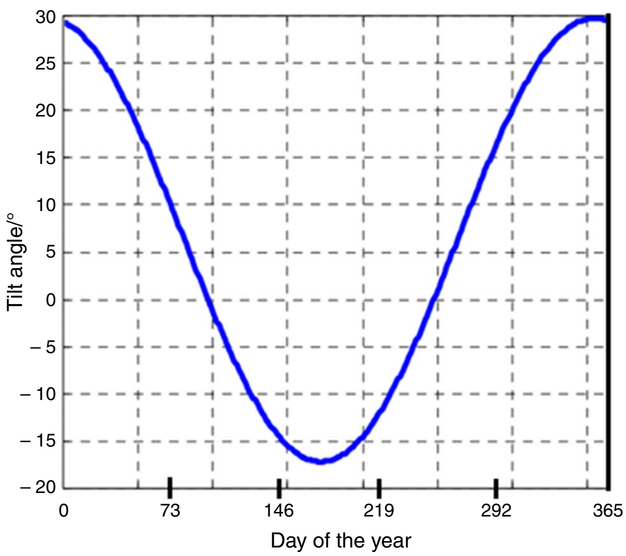


Fig. 3 Variation in tilt angles to capture maximum solar irradiance [65]

out the information on finding the behavior of PV panels with tilt angles adopting these three techniques. Further, the information provided in tabular form is enough for the reader to get an overall idea of the previous works without even properly reading the entire literature. This review article is divided into five main sections. In Sect. 2, the review of mathematical models generally employed for locating tilt angles is provided. In Sect. 3, the literature review of research work based on pure mathematical models is described. In Sects. 4 and 5, review of studies pertinent to computational and experimental analysis is provided in detail. In Sect. 6 of this article, the combined approach of these three or any two methods adopted to find the optimum angles is reviewed.

Governing equations for mathematical analysis

The total radiation (H_T) on the PV panel surface is given by Eq. (2) as follows:

$$H_T = H_B + H_D + H_R = (H_g - H_d)R_b + R_d H_d + H_g \rho \frac{1 - \cos\beta}{2} \tag{2}$$

Here, H_B is direct beam radiation, H_D is diffuse radiation, H_R is reflected radiation, H_g is global radiation in (Wh m^{-2}), ρ is the albedo of the ground, and R_b is defined as ratio of beam radiation between tilted surface and horizontal surface [51–56]. Now, R_b is given by

$$R_b = \frac{\cos(\varphi \mp \beta)\sin\omega_{ss} + \omega_{ss}\sin(\varphi \mp \beta)\sin\delta}{\cos\varphi\cos\delta\sin\omega_{ss} + \omega_{ss}\sin\varphi\sin\delta} \tag{3}$$

ω_{ss} is the sunset angle for tilted surface given by $\omega_{ss} = \cos^{-1}(-\tan\delta\tan\varphi)$, where φ is the location latitude, and β is the tilt angle of solar collector (rad), and δ is calculated using the following approximation:

$$\delta = 23.45 \sin\left(360 \frac{284 + n}{365}\right) \tag{4}$$

Here, n is the day of the year in number out of 365 days in a year. If the atmosphere is clear, then the diffuse radiation is calculated by Eq. (5) given by Liu and Jordon [57]:

$$R_d = \frac{1 + \cos\beta}{2} \tag{5}$$

The Equation which relates daily, hourly, and terrestrial irradiations is given by [32]:

$$\frac{I}{H} = (a_1 + b_1\cos\omega)\frac{I_o}{H_o} \tag{6}$$

where the coefficients $a_1 = 0.409 + 0.5016\sin(\omega_{ss} - \pi/3)$ and $b_1 = 0.6609 - 0.4767\sin(\omega_{ss} - \pi/3)\omega$ is the solar hour angle (rad). I is terrestrial hourly solar radiation on a horizontal surface (Wh m^{-2}), and I_o is extraterrestrial hourly solar radiation on a horizontal surface (Wh m^{-2})

Now, the relation between total terrestrial radiation and diffuse radiation is given by Eq. (7) proposed by Liu and Jordon [57]

$$\frac{H_D}{H} = 0.974 + 0.693\frac{H}{H_o} - 6.067\left(\frac{H}{H_o}\right)^2 + 6.416\left(\frac{H}{H_o}\right)^3 - 1.931\left(\frac{H}{H_o}\right)^4 \tag{7}$$

Here, H_o is extraterrestrial and H is terrestrial daily solar radiation on a horizontal surface in (W h/m^2)

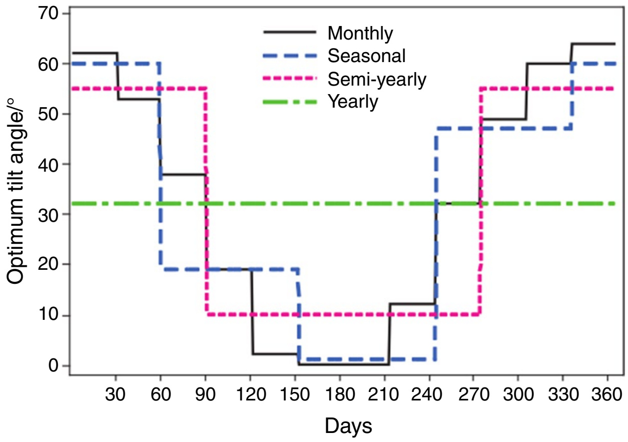


Fig. 4 Different tilt angles for four different aspects to obtain maximum solar energy in Tabass [72]

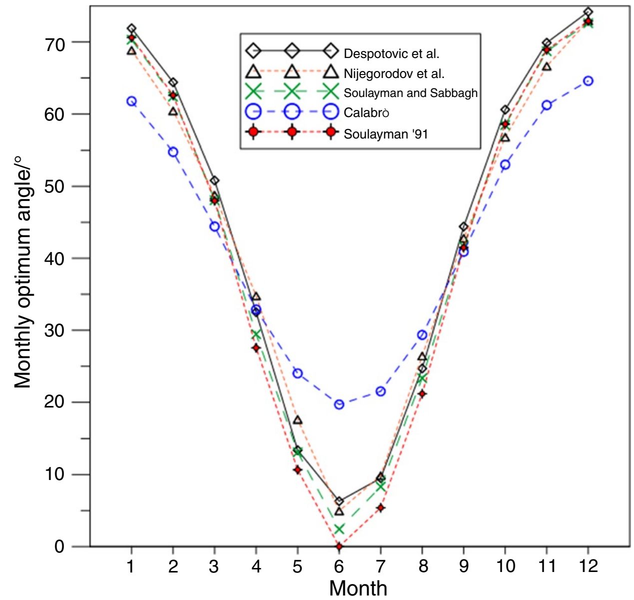


Fig. 5 Tilt angles variation to obtain maximum solar energy for different months obtained by Despotovic et al. [76], Soulayman and Sabbagh [78], Nijegorodov et al. [79], Calabrò [80], and Soulayman [33]

Mathematically locating of optimal tilts

Tsalides and Thanailakis [58] provided a common method to determine the optimum tilt angle in which the location latitude, orientation of the PV arrays, insolation conditions, and climatological situations were taken into account. Around 40–60% greater in the location latitude were found to be optimal tilt angles for azimuthal angles varying in 0° to ± 60° range. Linear relation exists between optimal tilt angle and clearness factor. The effect of tilt angle and azimuth angle on daily basis for PV panel was studied by Yakup and Malik [59]. Varying the tilt angle on monthly basis gives nearly same output relative to daily basis. 5% increased energy is obtained annually compared to fixed horizontal surface [59]. Total solar radiation on the surface of solar collector for an optimum angle was estimated by Ulgen [60]. The optimum tilt angles varies between 0° in June to 60° in December, whereas 55.7° is suggested during winter season, 18.3° in spring, 4.3° in summer, and 43° in autumn. Optimum tilt angles were obtained on monthly basis, seasonal basis, and yearly basis for Izmir, Turkey. In another work on Izmir, Turkey the best orientation for PV panel is found due south as suggested by Gunerhan and Hepbasli [61]. To improve the efficiency, the tilt angle should be fixed on monthly basis. The optimum tilt angle varying every day was also illustrated as shown in Fig. 2 [61].

Chang [62] reported that utilizing the extraterrestrial, predicted global radiation model and ten-year estimated data of solar radiation, the optimum tilt angle is found to be dependent on latitude. The measured data show that the optimal tilt angle is obtained with flatter plate, precisely for a location having polluted or cloudy environment [62]. The performance of PV panel of off grid system and grid-connected system based on variation in tilt angle was studied by Zhao et al. [63]. They analyzed the effect of weather and tilt angle on monthly basis and proposed a prediction model. To get the maximum output, the tilt angle has to be varied either on daily or monthly basis for Singapore. Using a mathematical model, optimum tilt angle monthly wise was calculated including the clear sky factor. The global solar irradiance and tilt angle change every day to obtain maximum solar energy. Tang et al. [64] proposed an analytical method to measure optimum tilt angles dependent on maximum yearly solar radiation for all-glass evacuated tube solar collectors. The optimum tilt angles are obtained 10° less compared to latitude for sites with latitudes greater than 30°. A set of optimum tilt angles during winter and for summer months are obtained to absorb maximum solar energy [64]. In northern Malaysia, the PV panel efficiency was analyzed for tilt angles − 17.16° to 29.74°, and it was observed that clear sky global irradiance can be effectively used for power generation. The tilt angles varied in a sinusoidal waveform shifting to the left at which the irradiance was maximum as shown in Fig. 3 [65]. The optimum angle varies between − 6.9° and 58.63° in June and January, respectively, in Ifsahan, Iran, as predicted by Pour et al. [66]. They used Liu and Jordon model for determination of optimum tilt angle considering the effect of azimuth angle. The energy collected based on yearly fixed tilt angle gives 8% less than the monthly fixed tilt angle [66].

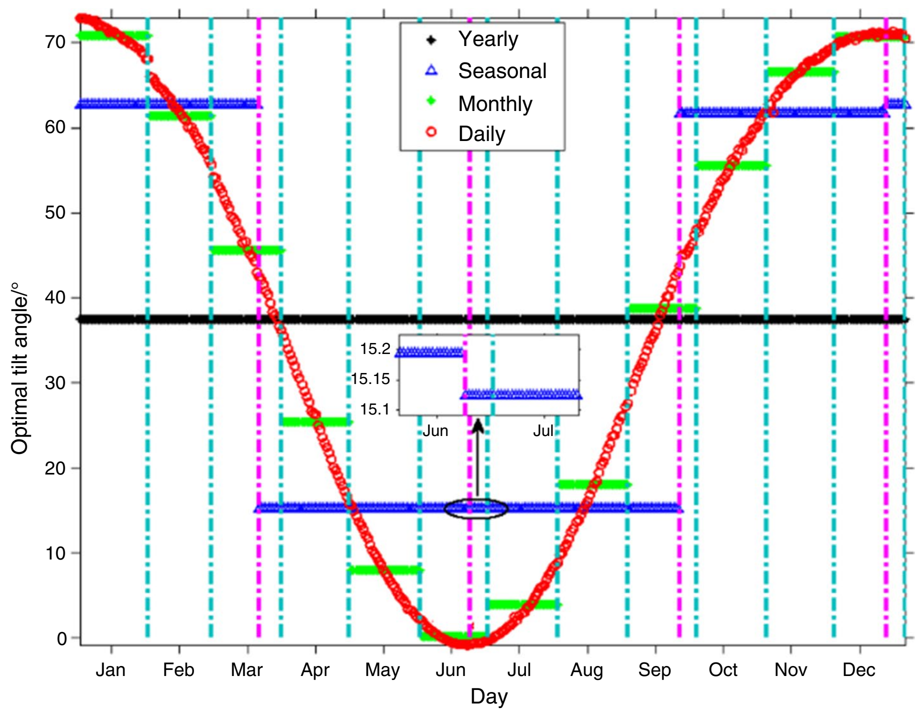


Fig. 6 Optimum tilt angles obtained for different time duration basis using support vector regression model and Bees algorithm [81]

Shading has hindering effect on performance of solar panels. Tilt angle and orientation help in reducing the shading effect that as studied by Elhab et al. [67]. Optimum tilt was checked in stepped, flat, and inclined fields in Kuala Lumpur. The worst effect of shading was seen in winter which reduced the solar collector performance. Sunderan et al. [68] showed that the energy gains of yearly optimum tilt angle for Ipoh, Malaysia, are 6.1% and 6.4% for monthly basis. The PV panel orientation was north ranging in April till August, and for the remaining months, it was south. They concluded that optimum tilt angle and orientation improve the generation of power of stand-alone photovoltaic electricity generation systems. Five different sites of Malaysia were chosen for study of effect of tilt angle on PV performance by Khatib et al. [69]. For optimization of tilt angles, anisotropic models used were Liu and Jordan. For these five sites, changing the tilt angles on monthly basis gives at least 5% extra output [69]. Agarwal et al. [70] determined the optimal tilt and orientation angle for PV panel at different sites in India for specific period and monthly basis. The results show that varying the tilt angle every month gives approximate maximum energy output that could be obtained by varying the tilt angle on daily basis. For the shading-type building-integrated photovoltaic claddings, Sun et al. [71] evaluated optimum tilt angles for Hong Kong. At a tilt angle of 10°, maximum energy output was obtained installed on south facades. For varying wall utilization fractions and orientations, optimum tilt angles obtained are different for the PV panel which lies between 30° and 50°. Khorasanizadeh et al. [72] determined effect of south-facing PV panel surfaces in Tabass for different time periods. 0° is the optimum tilt angle in June, whereas it is 64° in December as shown in Fig. 4. 32° was observed as optimum angle for yearly basis. 23.15% gain was obtained for monthly basis and semi-yearly tilt of 10° gives the same output.

To increase the electricity generated from PV module, Drury et al. [73] used tracking systems. Horizontal one-axis tracking system gives 12–25% increased output compared to south-facing 25° fixed tilt angle, whereas two-axis system gives up to 30–45% improvement. Khoo et al. [74] placed the PV system facing in all directions (east, west, north, and south in Singapore) using Perez model. East-faced module provided the highest annual output. This work was further extended for 10° tilt facing all four directions in which 10° east gave the highest yield. Hartner et al. [75] analyzed orientation and tilt angles for 23 sites of Austria and Germany. Adjustments in installations angles of PV panels improved the output energy thereby reducing the electricity cost. For further improvement in PV panel output, orientation angles were adjusted toward east and also steeper tilt provided better energy output. A comparative analysis for tilt angles fixed from yearly basis till daily and fortnight basis for the performance of PV panels is reported in [76]. 5.98% improvement in energy gain is observed for yearly basis, 13.55% for seasonal basis and 15.42% for monthly basis optimum tilt angles. The tilt angle based on daily to yearly basis

Table 1 Details of data/models used for mathematical modeling

Tilt angles considered	Location	Latitude Ø/N	Longitude/E	Average solar radiation/kWh m^{-2}	Optimum tilt angle (monthly)	Software/Approach	Model/algorithm	References
40°–70°	Greece	37.5°	23.4°	4.2	46°–58°	Least square method	Liu and Jordan's insulation model and Klien model	[58]
– 35° to 35°	Brunei Darussalam	4.9	115	5.5	1.6°–32.3°		Empirical data	[59]
0°–90°	Izmir, Turkey	36°	42°	3.6	0°–61°		Isotropic model	[60]
0°–90°	Izmir, Turkey	36°	42°	3.6	Ø ± (15°)		Empirical data	[61]
– 20° to 60°	Taiwan	25°	121.3°	2.4–4.1	– 15° to 50°		Empirical data	[62]
0°–90°	Singapore	1.3°	103.8°	2.84	0.11°–25°		ARMA	[63]
0°–90°	China	39.5°	116.2°	4.6	10° less than the site latitude for T-type and 20° less than the site latitude for H-type		Empirical data	[64]
– 20° to 30°	Perlis, Malaysia	6.29°	100.16°	4.17–5.08	– 17.16° to 29.74°		Empirical data	[65]
– 10° to 90°	Isfahan, Iran	32°	51°	8.9–10.11	0.15°–57.74°		Liu and Jordan model, Klein model, Hay model	[66]
10°–30°	Kuala Lumpur, Malaysia	3.8°	101°	4–5	10°	Visual Basic Application (VBA) programming	Cooper's equation	[67]
– 20° to 30°	Ipoh, Malaysia	4.35°	101.05°	4.2–5.1	$\emptyset - \delta$			[68]
0°–35°	Malaysia	4.35°	101.05°	4.2–5.1			Liu and Jordan.	[69]
0°–60°	Delhi and Nandha, India	28.7°	77.1°	2.6	28.9°–31.7°		Liu and Jorden, Reindel, Hay and Badescu models.	[70]
0°–90°	Hong Kong	22.2°	114.1°	2.7–4.6	10°			[71]
0°–90°	Tabass, Iran	33° 3	56.5°	2.8–5.4	0°–64°			[72]
25°, 1-axis and 2-axis tracking	USA	37°	95.7°	2.9–6.2	Tracking system		PVWatts model	[73]
10°–40°	Singapore	1.3°	103.8°	2.84	10° east (yearly)		Sky models	[74]
0°–90°	23 locations of Austria and Germany				10°–35°		Isotropic diffuse radiation	[75]
0°–90°	Belgrade, Columbia	44.4°	20.4°	3.98	43.55°		Liu and Jorden	[76]
0°–90°	Sindh, Pakistan	25.07°	67.38°	6.5–7	0° (May–July), 49° (November–January		Common correlations	[77]
0°–70°	9 cities of USA	38.53°	77.01°	2.9–6.2	Varies for each city	LIBSVM software in MATLAB	Bees algorithm and support vector regression model	[81]

Table 1 (continued)

Tilt angles considered	Location	Latitude Ø/N	Longitude/E	Average solar radiation/kWh m^{-2}	Optimum tilt angle (monthly)	Software/Approach	Model/algorithm	References
10°–90°	State capitals of India	28.7°	77.1°	2.6	30°–32°		HDKR (Hay-Davies-Klucher-Reidnl) model	[82]
10°–90°					38°–40°		HDKR/shadow model	[83]

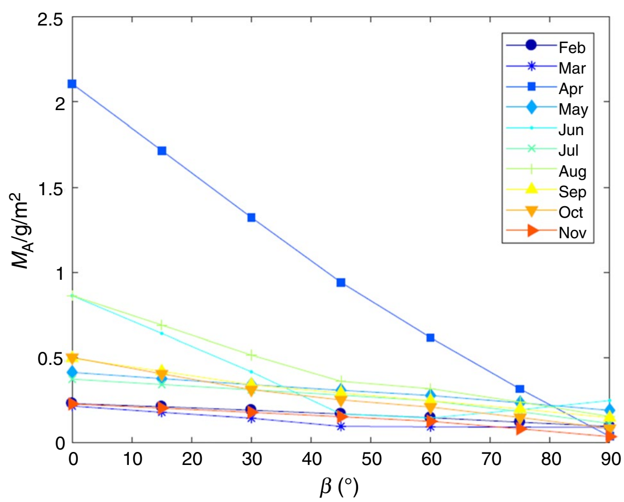
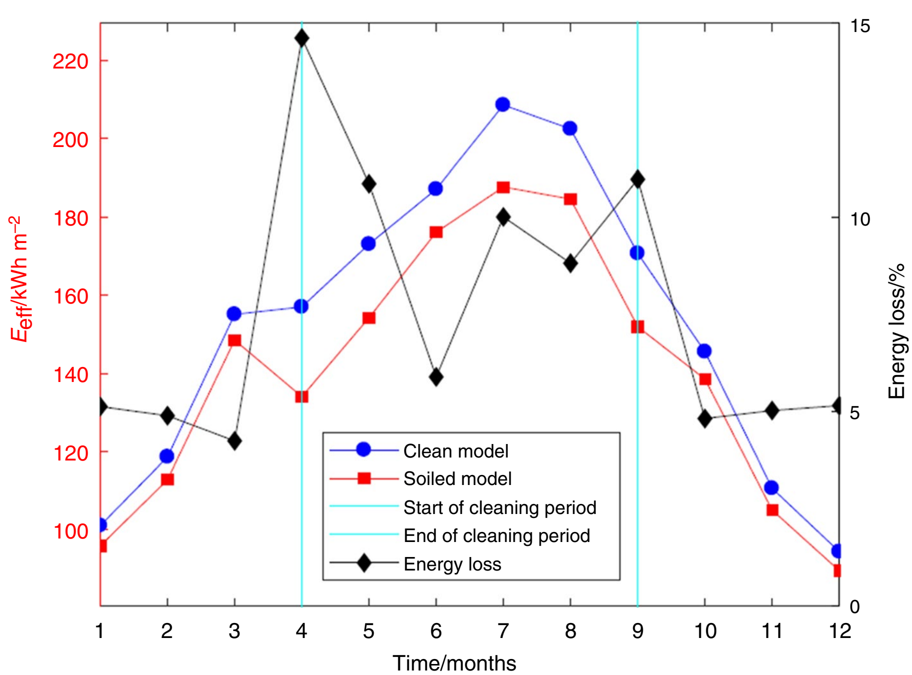


Fig. 7 Soiled particles mass (M_A) as a function of tilt angles (β) in different seasons [84]

required for maximum energy generation keeps on changing. The results related to optimal tilt angles obtained using the explained procedure mentioned in [76] verified many previous works reported in the literature as shown in Fig. 5. 0° is the optimum tilt angle in May, 49° in June and July, and also the optimum angle for yearly basis is 23° which was found to be close to location latitude [77].

Akhlaghi et al. [81] attempted to avoid using solar tracking which are cost inefficient and fixed tilt angle which causes loss of solar power. They proposed to use a limited number of tilt angle adjustments in a day to avoid the mentioned issues. Using different algorithms like Bee optimization algorithm, the tilt angle was found for different time durations as shown in Fig. 6. Investigation of building-integrated PV panel under the influence of adverse shadow effect is reported in [82]. More recently, building-integrated PV panel considering shadow effect by incorporating modified Hay, Davies, Klucher, Reindl/shadow model

Fig. 8 Effective energy output (E_{eff}) and loss in energy due to soiling and clean PV model [84]



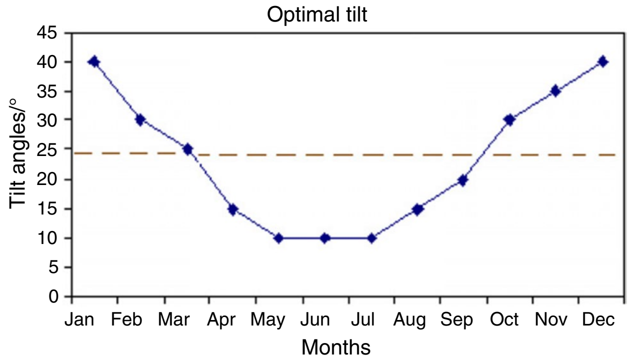


Fig. 9 Average optimum tilt angle for PV module output energy in Madinah at each month [88]

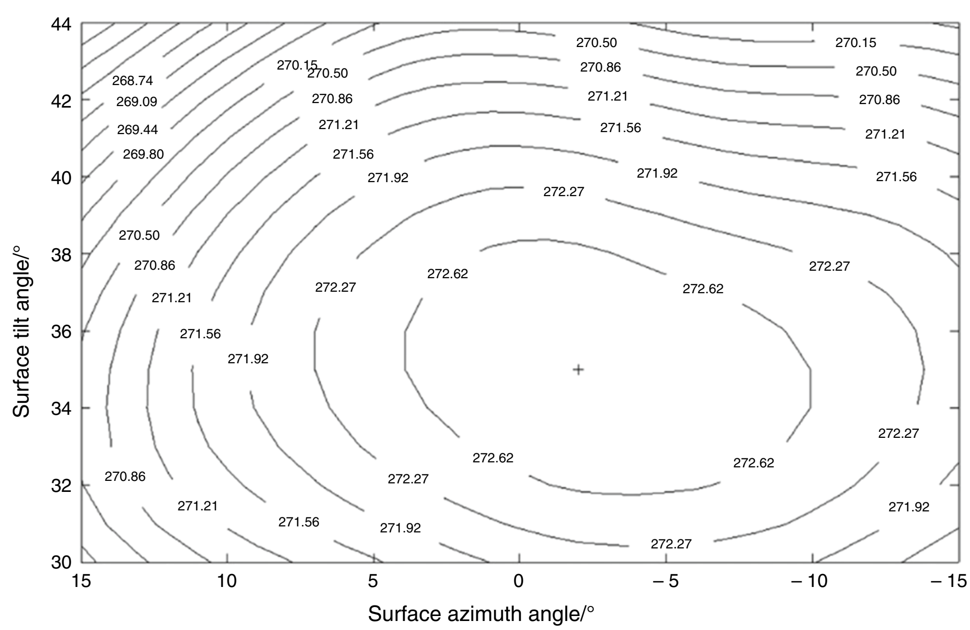
was mathematically studied by Yadav et al. [83]. In Table 1, the important details of mathematical analysis carried out are mentioned. The type of model used, location, tilt angles considered and optimal tilt angle obtained are also provided. Conceição et al. [84] studied analytically and developed a model suitable for solar irradiance considering soiling effect. Effect on optimal tilt angles with soiling effect was studied simultaneously on PV panel output. Consideration of seasonal soiling effect provided an understanding of multiple tilt angles to increase the annual energy output. The mass accumulated in each month around the year as a function of tilt angle (β) is shown in Fig. 7. Figure 8 shows the cleaning period required for increasing the efficiency in specific months.

Computational determination of optimal tilts

For a thermo-siphoning solar PV panel in Jordon, Shariah et al. [85] employed annual solar fraction as an indicator for optimum tilt angle. The tilt angles vary between Ø to $\left(Ø + 20°\right)$ in a high solar fraction system. The author recommended to consider the effect of climate and latitude on optimum tilt angle. The performance of PV modules at different tilt angles was studied using a mathematical model developed in FORTRAN in connection with TRNSYS simulation. Tilt angles in the range 20°–30° was considered to be optimum for the PV modules at which maximum yearly PV module energy was found to be maximum. The tilt angle and orientation effect on output obtained from PV module was also illustrated in [86]. Optimum tilt angles during summer months were completely different than the winter months. The difference during these months leads to development of a semi-fixed PV panels which needs to change twice in a year [87].

1% reduction in energy is obtained if the tilt angle is fixed seasonally compared to monthly basis. Similarly, fixing the tilt angle for a year gives 15% reduction compared to fixed on monthly basis. Tilt angle for yearly basis is equal to location latitude [89]. The optimum tilt angle found was equal to location latitude of Madinah as shown in Fig. 9. Yearly-based optimum tilt angle can be used if manufacturing/installation cost is required to reduce, else can switch to monthly/seasonal basis [88]. Rowlands et al. [90] modeled and determined solar radiation data and analyzed PV panel performance in Canada. The optimum tilt angle was seen quite lower than latitude of 45°, and the azimuth angle

Fig. 10 Energy produced in kWh for different tilt angles and azimuthal angles [90]



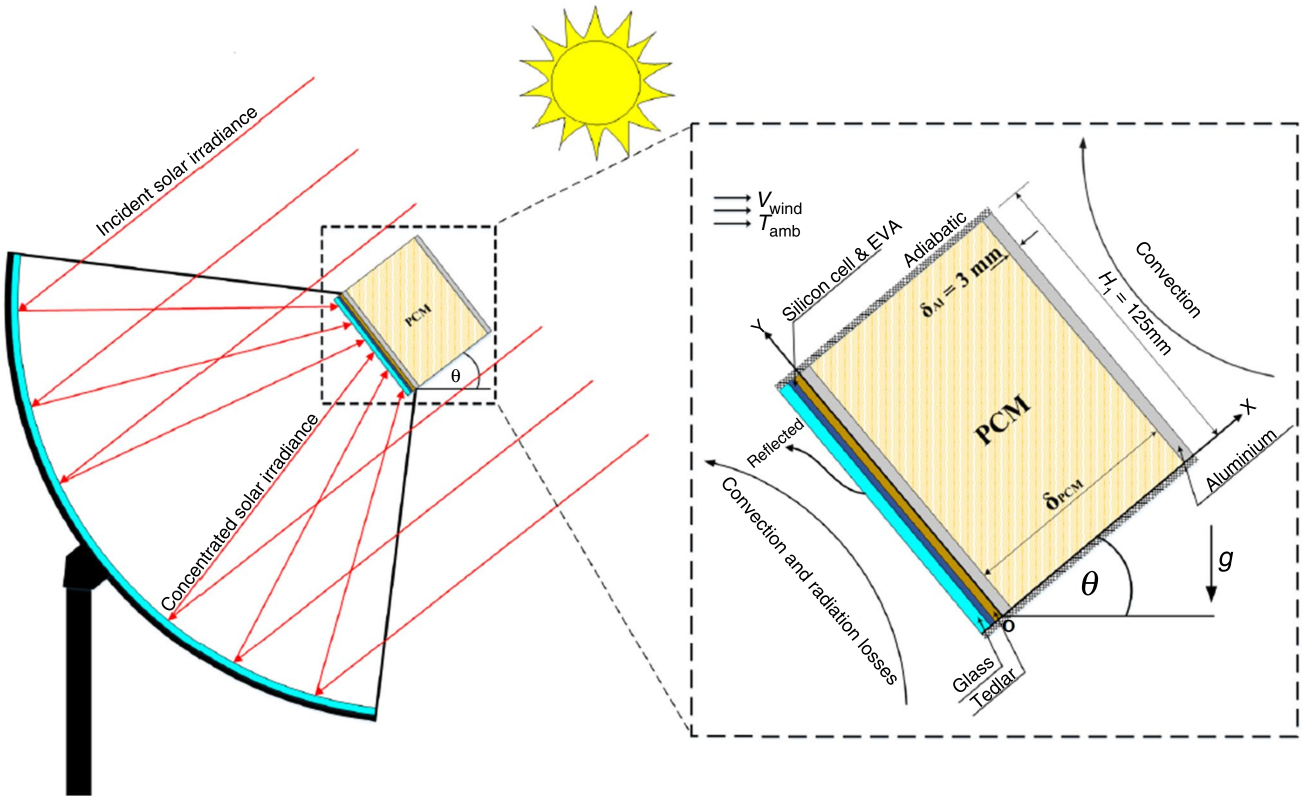


Fig. 11 Model of concentrated PV panel integrated with PCM [92]

Fig. 12 Computational model of PV panel with PCM [92]

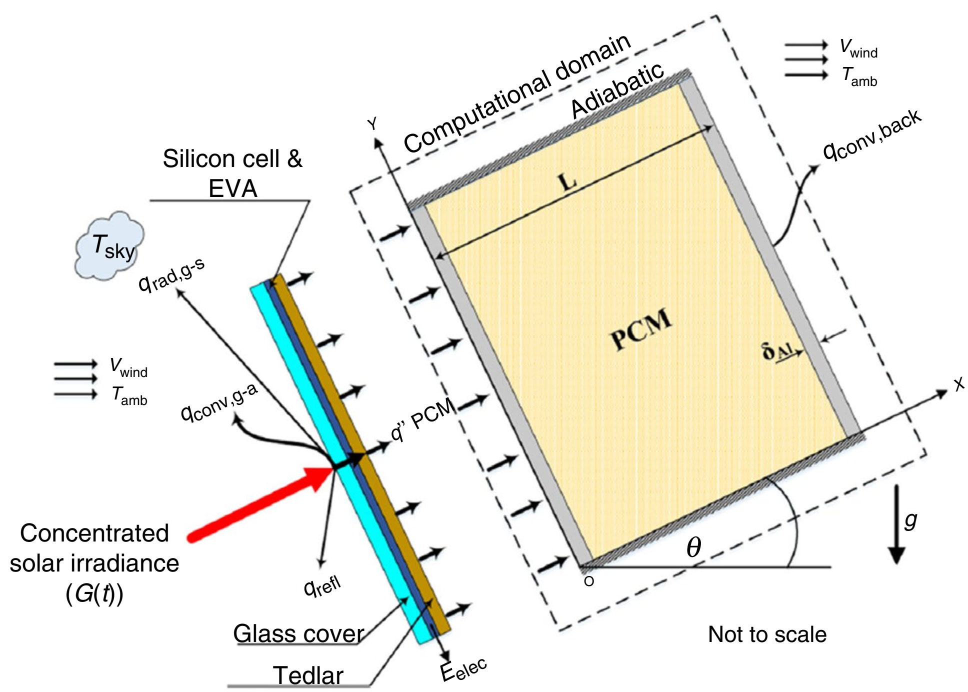


Table 2 Details of computational analysis carried out to find optimal tilt angles

Tilt angles considered	Location	Latitude Ø/N	Longitude/E	Average solar radiation/kWh m^{-2}	Optimum tilt angle (monthly)	Method	Software/Approach	Model/algorithm	References
0°–90°	Jordon	31.5°	35.5°	5.5	$Ø$ to $(Ø + 20°)$	Computational	TRNSYS		[85]
0°–90°	Cairo, Egypt	30.3°	31.4°	2–7.8	20°–30°	Computational	TRNSYS		[86]
5°–65°	Italy	41.8°	12.5°	1.27–2	$Ø - (27°)$	Computational		Sky radiance	[87]
0°–90°	New Delhi	28.7°	77.1°	3.88	13°–47.5°	Computational	MATLAB and MS Excel	Diffuse radiation model	[89]
0°–90°	Madinah, Saudi Arabia	24.3°	39.4°	5–7.5	12°–37°	Computational	MATLAB	Diffuse radiation	[88]
30°–45°	Ontario, Canada	51.2°	85.3° W	4.57–5.35	32°–38°	Computational	ESP-r simulation program	Watsun-PV	[90]
− 90° to 90°	Reunion Island, France	− 18.8°	55.3°	4.7–6.1	− 22.5° to 24.3°	Computational	Energy-Plus and GenOpt	Hooke–Jeeves	[91]
	Many locations of US				23-° 40°	Computational	solaR package	Hay and Davies diffuse model	[93]
0°–90°	Typical urban area				discrepancy	Computational	Developed program	Modified anisotropic sky model	[94]
0°–90°	Bucaramanga, Colombia	7.1°	73.1° W	4.8–5.34	Equal to latitude	Computational	Virtual tool PVsyst		[96]
0°–90°	–	–	–	–	–	Computational	ANSYS Fluent	–	[97]
− 45° to 90°	–	–	–	–	45°	Computational	ANSYS Fluent	SIMPLE, PRESTO	[92]
25°–155°						Computational	ANSYS Fluent	SIMPLE	[98]
15°–75°						Computational	ANSYS Fluent	SIMPLEC, PRESTO	[30]
0°–90°	Pontianak, Kota Kinabalu, Tacloban	0°, 5°, 58°	109°, 116°, 125°	4.85–5.52	15°–45°	Computational	HOMER	HDKR model	[99]
0°–90°	Baghdad, Diyala, Tikrit	33.2°, 33.1°, 34.3°	44.2°, 45.4°, 43.4°	7.5–23.5 MJ/m^2	15°–55°	Computational	EES	Bernard-Menguy-Schwartz (BMS) model	[100]
− 90° to 90°	All countries				Different for each countries	Computational	PVWatts	Weather–climate–air pollution model GATOR-GCMOM	[101]

Table 2 (continued)

Tilt angles considered	Location	Latitude Ø/N	Longitude/E	Average solar radiation/kWh m^{-2}	Optimum tilt angle (monthly)	Method	Software/Approach	Model/algorithm	References
0°–90°	Jakarta, Jayapura, Kuala Lumpur, Singapore city, Bangkok	6.17°, 2.59°, 3.13°, 1.35, 13.75°	106.86°, 140.66°, 101.68°, 103.81°, 100.5°	3.1–5. 2	45°	Computational	Valentin software	–	[102]
0°–90°	Saudi Arabia	24.39°	46.46°	7.44–6.22	8°–55°	Computational	MATLAB code	In-house model	[103]

was close due south. The energy produced for different tilt angles and azimuthal angles using a single panel is shown in Fig. 10. Hooke–Jeeves algorithm was employed to determine the optimum tilt angle to get maximum energy generation of PV systems located in Reunion Island, France, by Bojic et al. [91]. They found disturbing results related to optimum tilt angle and latitude implying the necessity of evaluating the optimum tilt angle for each location to get maximum performance of the system. Around 5% increase in energy gain is obtained for optimum tilt angle throughout the year.

For over 1020 locations of US, the optimal azimuth angle to get maximum energy is 187°–188°, and to get maximum economic output, the tilt angle is 200°–231°. For azimuth angle within 10° of south, maximum output is obtained for rest of US [93]. Siraki and Pillay [94] developed a modified Hay, Davies, Klucher, Reindl model (anisotropic sky model [95]) to calculate the optimum tilt angle which also

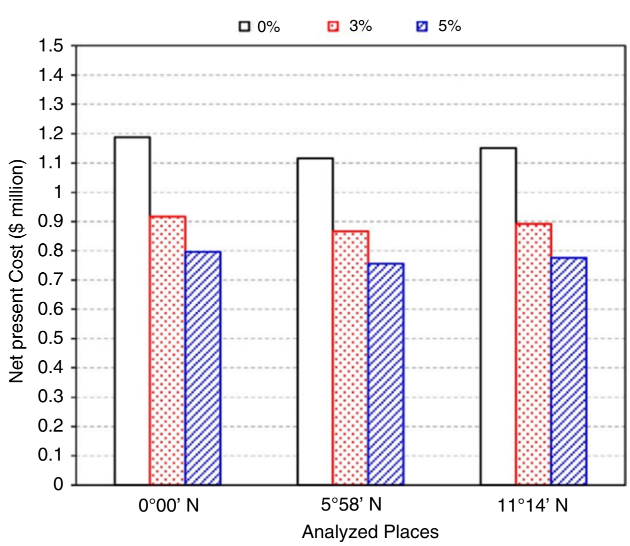


Fig. 13 Net present cost at different locations of equator and for different annual interest rates of 0%, 3%, and 5% [99]

considers the adjacent buildings effect. The optimum tilt angle was obtained near to the location latitude for small latitudes. Smaller optimum angle was seen for higher latitude compared to location latitude indicating that the optimum tilt angle and orientation effect the maximum performance of PV panels. Vargas et al. [96] studied the effect of tilt angles and azimuth on performance of PV panels using software. Azimuth of 0° and tilt same as location latitude give maximum benefit. Few others include study on effect of tilt angle and operating conditions of a PV module combined with phase-change material (PCM) [97] and performance of concentrated-type inclined PV system integrated with PCM [92]. For the PCM analysis, commercial software ANSYS Fluent was used for modeling the PV panel system, as shown in Figs. 11 and 12. Effect on performance of ground-mounted PV panel by particle size of dust deposition and tilt angles was investigated by Lu and Zhao et al. [98], and numerical analysis on effect of tilt angle and velocity of wind on thermal behavior of PV panels within the glazed cavity is reported in [30]. In Table 2, the important details of computational analysis carried out are mentioned. The type of model used, location, tilt angles considered and optimal tilt angle obtained are also provided.

Lau et al. [99] studied the effect of tilt angles, ambient temperatures, and orientation on PV arrays producing electricity and the total net present costs (NCP) of hybrid PV system. At three different locations, 10–50 °C ambient temperatures and 0°–90° tilt angles were analyzed. 55% and 18% reduction in electricity due to tilt angle and ambient temperature variation were obtained. The annual interest rates were found to be inversely proportional to NCPs as shown in Fig. 13. The tilt angles, however, were found to have minimal effect on electricity production of PV arrays as shown in Fig. 14 for different locations. At nearer locations, the electricity production was found to be almost same. Ali Morad et al. [100] obtained yearly and monthly optimal tilt angles for different cities of Iraq. Using the Fortran-based computer program,

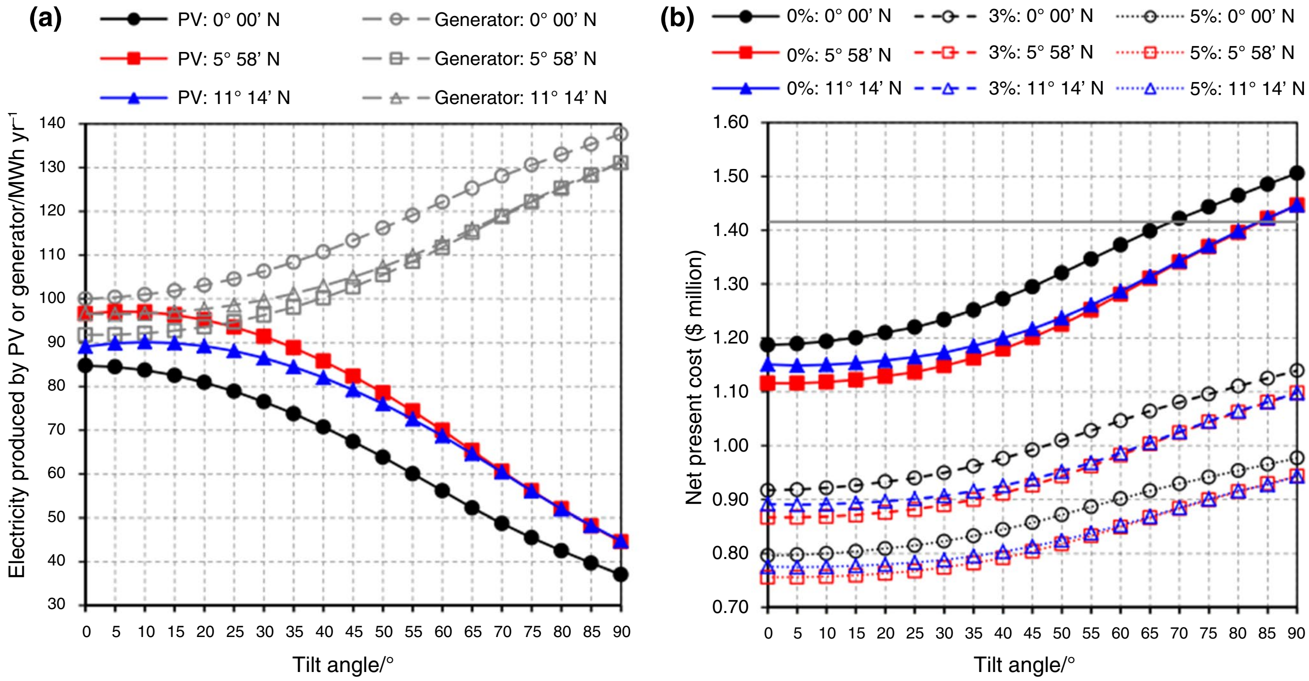
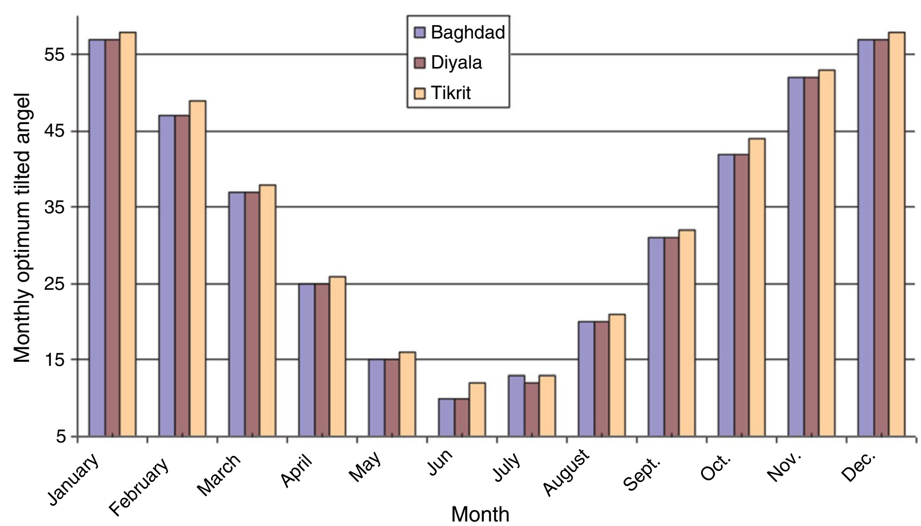


Fig. 14 Electricity produced for different tile angles and locations [99]

Fig. 15 Optimum tilt angles for three cities of Iraq [100]



the mathematical models were solved. Different optimal angles were found for every month depending upon the solar power intensity. The optimal tilt angles obtained for every month is shown in Fig. 15 for different cities of Iraq. Jacobsen and Jadhav [101] provided the optimal tilt angles of PV system for all the countries using PVWatts program of National Renewable Energy Laboratory (NREL). For the optimal tilt angles for all the countries, a third-order polynomial fit was derived as a function of latitude. When the latitude is above 40° N, the polynomial fit matches more properly as shown in Fig. 16. Then, using global three-dimensional GATOR-GCMOM (Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale, and Ocean Model) model and the obtained optimal tilts, annual ratios of radiation normally incident to optimally tilted two-axis tracked panels, one-axis

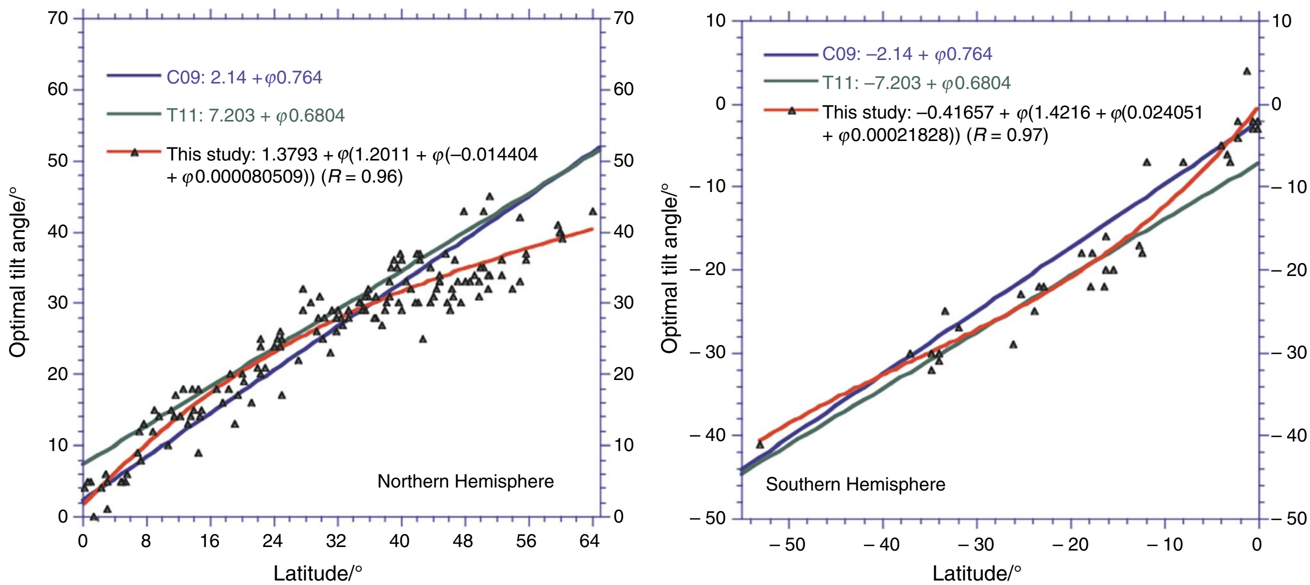


Fig. 16 Location of optimum tilt angles for countries all over the world [101]

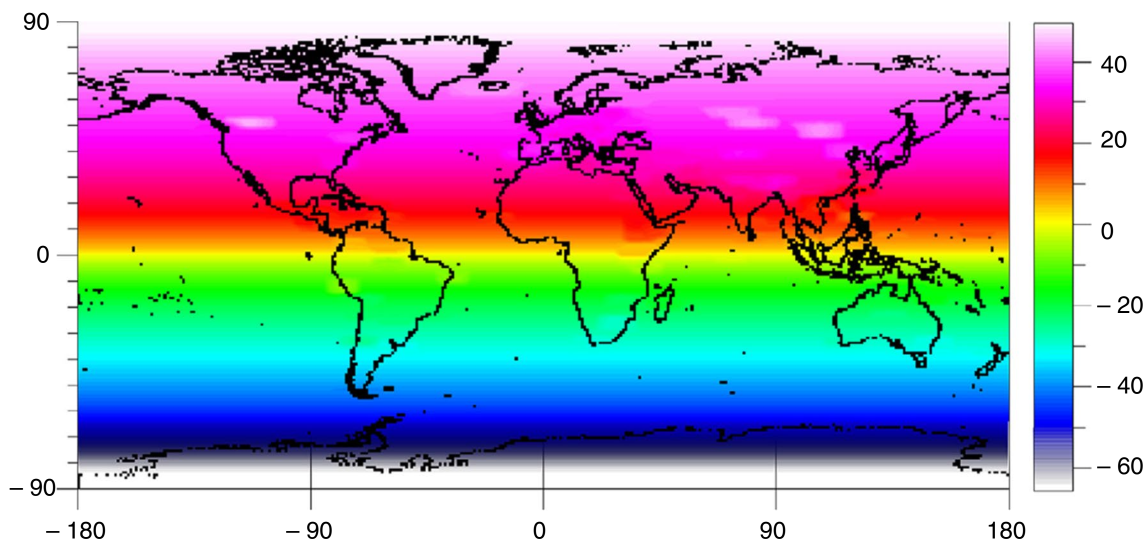


Fig. 17 Using GATOR-GCMOM model optimum tilt angles worldwide [101]

horizontally tracked, one-axis vertically tracked comparative to horizontal panels. Two-axis tracking is different than one-axis tracking, and one-axis in horizontal tracking mode provides more output than one-axis vertical tracking. Compared to optimal tilts, the tracking provided better output above 75° N and 60° S. The simulation of optimal tilts using the GCMOM model for all the countries is shown in Fig. 17. Kumar and Dinniyah [102] used net-metering option in different cities of southern Asia to generate grid-based electricity. For different PV strategies, simulation was performed using software available online. In the order of Si-amorph, Si-mono, and Si-poly,

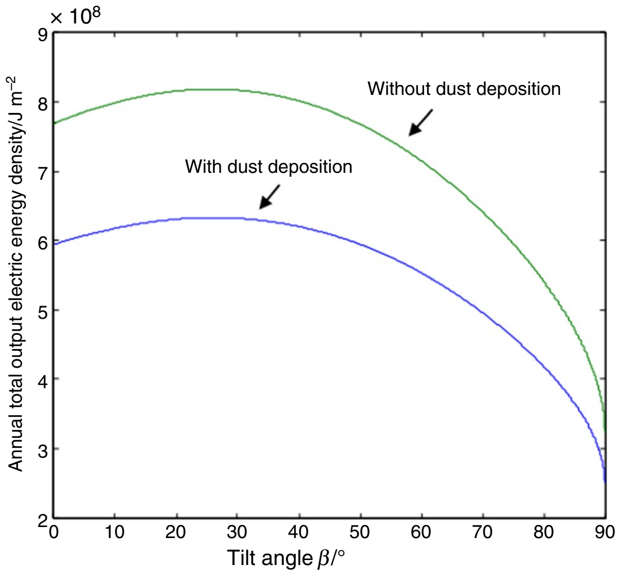


Fig. 18 Tilt angle and dust deposition effect on total electric energy output [107]

the performance of PV panels was obtained. The energy generation is found to be a pure factor of tilt angles for these different cities. Garni et al. [103] estimated electrical energy output from 18 different places of Saudi Arabia for the purpose of solar plants at utility scale. For different azimuth and tilt angles, the optimum energy was determined. Influence of non-optimal tilt on energy yield was analyzed. Compared to April and September, in March and October, the yield is higher. For each month, the optimal tilt and azimuth angles were separately determined. 4.01% increase in yield was obtained when the tilt angle was adjusted on monthly basis.

Experimentally locating of optimal tilt angles

Soleimani et al. [104] experimented with PV modules for different tilt angles and effect of air pollution. 30° tilt angle was found to be optimum for grid-connected application, and 60% reduction in solar output was seen due to air pollution. Optimum tilt angles annually for PV panel were studied by Kacira et al. [105]. Tilt angle and optimum angle equal to latitude were 3.9% and 1.1%, respectively, to get maximum energy generation. Monthly adjustments of about 10° are found to be necessary for obtaining maximum solar irradiance. Different adjustments for optimum monthly basis and for yearly basis were obtained, as reported in [105]. Optimum tilt angles at Kuala Lumpur, Malaysia, are approximately equal to the latitude as found by Elhassan et al. [106]. These angles are for building-integrated PV panels inclined in the east, west, and north directions.

Fahl and Ganapathisubbu [108] determined optimum tilt angle between 15° and 17° for Bangalore, India, for south-facing collectors. The incident solar radiance is observed to be same with a fluctuation in optimum tilt angle of ± 3°. The output from the PV collector obtained was 10% more compared to horizontally oriented panels. By fixing, tilt angles and varying tilt angles on monthly basis produced marginal benefit relative to horizontal orientation, whereas for consistent tracking systems, up to 35% benefit was seen. PVT hot water system on high building facades was installed by Sun et al. [109] to study the effect of tilt angles. PVT modules with different connection (parallel or series) modes have considerable effect on its performance. 20° tilt angle gives maximum benefit of total energy. 40° tilt angle was considered as optimum if projection length and total energy benefit are required together. Similar other works reported on finding, optimal tilt angle to obtain maximum performance of solar PV

Table 3 Details of experimental analysis related to optimal tilt angles of PV panels

Tilt angles considered	Location	Latitude Ø/N	Longitude/E	Average solar radiation/kWh m^{-2}	Optimum tilt angle (monthly)	References
0°, 23°, 29°, 35° and 42°	Tehran	35.7°	51.4°	4.5–5.2	30°	[104]
0°–60°	Sanliurfa, Turkey	37.9°	38.5°	5.1	13°–61°	[105]
15°–30°	Kuala Lumpur, Malaysia	3.8°	101°	4–5	Nearly equal to latitude	[106]
0°–30°	Bangalore, Karnataka	12.5°	77.3°	3.3–7.5	15° and 17° (fixed)	[108]
10°–80°	High-rise residential buildings				40° (fixed)	[109]
10°–90°	Hangzhou, China	30.23°	120.1°	6.14–3.18	26.06°	[107]
15°–45°	Egypt	24.05°	32.53°	24.46	15°–30°	[110]
30°, 45°, and 60°	Guangzhou	23.07°	113.1°	Indoor study	–	[111]

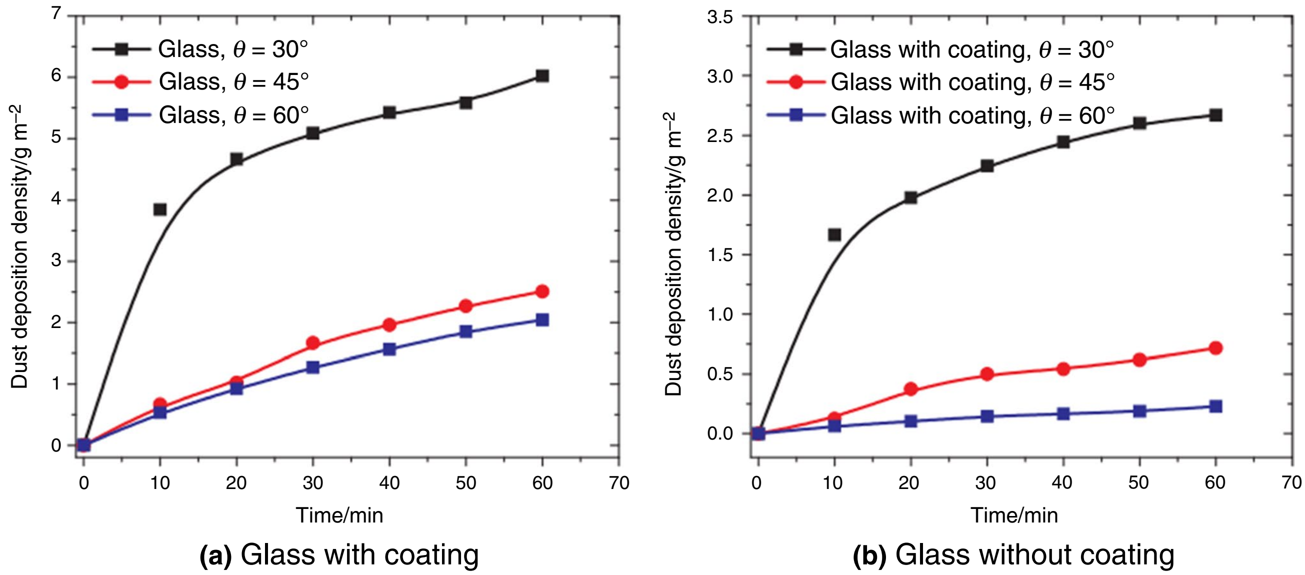
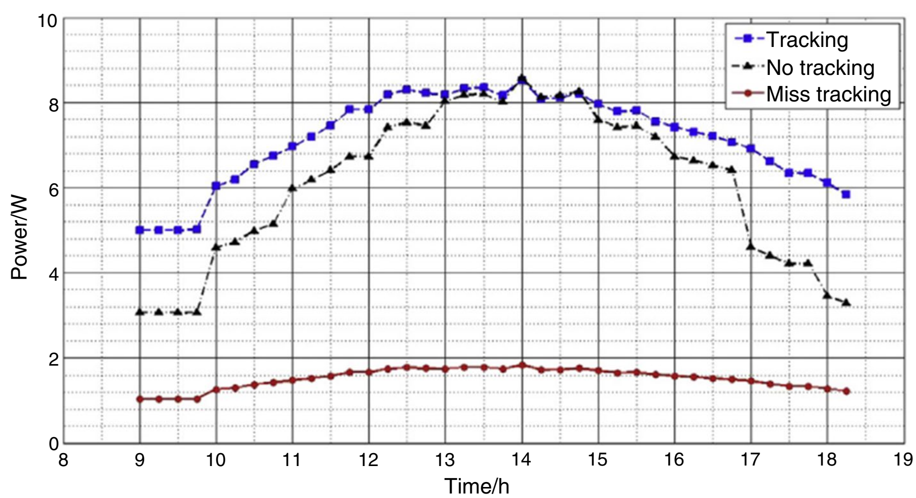


Fig. 19 Dust deposition at different tilt angles as a function of time [111]

Fig. 20 Power gain obtained in Germany for different tracking conditions on July 15, 2013 [115]



panel includes study by Xu et al. [107] on effect of dust deposition on a soiled PV panel. Analysis of dust deposition on PV module installed in desert region is studied in [110]. The effect of dust and tilt angles is shown in Fig. 18. In Table 3, the important details of experimental analysis carried out are mentioned. The type of model used, location, tilt angles considered and optimal tilt angle obtained is also provided.

Zhang et al. [111] analyzed the deposition of dust particles on the surface of solar cell glass conducting study indoor. The transparent glass of the PV module was made of super-hydrophobic coating and with no coating. Tilt angles were varied, and the dust density deposited in the surface of glass was measured. The efficiency reduced in PV panels due to dust deposition was analyzed at different tilt angles. Using the super-hydrophobic coating on glass the surface can be made to deposit very less dust particles due to low adhesion. Relative to hydrophobic coating, the super-hydrophobic coating showed better performance. The dust deposition density on the glass cover having no coating and

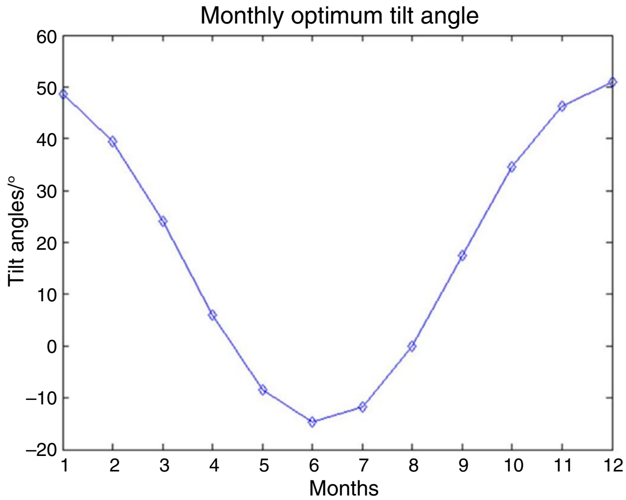


Fig. 21 Optimum tilt angles for Jeddah city throughout the year [116]

super-hydrophobic coating for different tilt angles is shown in Fig. 19.

Combined experimental, computational and mathematical methods

In Taipei region, Chang et al., [10] employed orthogonal array experiment technique and an ant direction hybrid differential evolution algorithm to determine tilt angles for PV modules. Ant colony method was employed to measure the optimum tilt angle. This method was found to be faster than genetic algorithm method. Beringer et al. [15] determined performance of PV panels at different tilt angles employing eight multi-crystalline silicium solar cells. They found the optimum tilt angles in the range 0°–30° on yearly basis. The maximum difference in the performance was found to be 6% for the tilt angles considered. In Vaal Triangle, South Africa, the optimum tilt angles were found to be 26° and 36° measured analytically during winters by Asowata et al., [112]. Equations were used for different tilt angles based on mathematical models to evaluate maximum power output of a PV panel. Xianping [113] used Hay's model of sky in combination with standard equations to measure monthly and yearly optimum tilt angle. Yearly tilt angle was found to be 19.22° for Changsa, China. 2.2% and 5.2% improvements in output were seen by fixing it on yearly and monthly basis, respectively, compared to tilt angle fixing to location latitude. In Greece, summer-only applications of solar PV panel being common were exploited for the specific period by Kaldellis and Zafirakis [114]. An optimum tilt angle of 15° proved to be best for the summer period to get the maximum output energy.

Solar tracking helps in improving the PV module efficiency, but where and when?, was the problem addressed by Eldin et al. [115]. Mathematically, the PV module performance was determined validating with experimental work under hot and cold region conditions, for tracking, miss tracking, and no tracking as shown in Fig. 20. It was found that tracking helps in obtaining 39% electrical energy gain in cold cities like Berlin, Germany, and in hot cities like Aswan, Egypt; the gain is just 8% due to PV panels overheating. Up to 10% of energy is required in solar tracking, and hence in hot cities, it is not feasible. The optimum tilt angles in various cities of Saudi Arabia were investigated using MATLAB and validated experimentally by Kaddoura et al. [116]. Using solar radiation data available from NASA, optimal tilt angle was determined by maximizing solar radiation. It was observed that by adjusting the tilt angles six times in a year, up to 99.5% incident solar energy can be harvested. Using the MATLAB-based optimization code developed, the optimum tilt angles obtained for Jeddah city is shown in Fig. 21. Jacobson and Jadhav derived a third-order polynomial relationship between optimal tilt angles and latitude considering the optimal tilt angles across different countries throughout the world [101]. Another similar study related to building modeling for solar power utilization through PV panels taking tilt angle into account was modeled using BIM software [117]. In Table 4, the important details of combined experimental, numerical, and mathematical analysis carried out are mentioned. The type of model used, location, tilt angles considered and optimal tilt angle obtained are also provided.

Zsiborács et al. [31] compared experimental and simulation results of tilt angles and dual-axis tracking features of three modules, namely amorphous silicon (a-Si), polycrystalline (p-Si), and mono- (m-Si) modules. Specific energy generation from the PV modules was compared using the dual-axis method. The simulation results were found to be less accurate than the real experimental data. Based on the results and favorable values from the simulation results, amorphous and crystalline modules can be decided. In Fig. 22, the dual-axis tracking, tilt angle, and orientation for the three PV modules are presented. The difference in output obtained from simulated and real data is compared

Table 4 Details of combined experimental, numerical and mathematical analysis

Tilt angles considered	Location	Latitude Ø/N	Longitude/E	Average solar radiation/kWh m^{-2}	Optimum tilt angle (monthly)	Method	Software/Approach	Model/algorithm	References
5°–75°	Taipei region	25°	121.4°	2.4–4.1	20°–23° annually	Experimental and computational		Ant direction hybrid differential evolution algorithm	[10]
0°–70°	Hannover, Germany	52.2°	9.4°		0°–30° in summer and 50°–70° in winter	Experimental and computational	INSEL	Newton–Raphson method	[15]
16°, 26° and 36°	Vaal Triangle, South Africa	26° south	27° east	3.82–4.37	26° and 36°	Experimental and mathematical			[112]
0°–90°	Changsha, China	28.2°	112.9°	5.5	2°–35°	Mathematical and Computational	MATLAB	Anisotropic Hay's model	[113]
0°–75°	Athens, Greece	37.9°	23.7°	4.2	15°	Experimental and mathematical			[114]
–	Berlin (Germany) and Aswan (Egypt)	52.3° and 24.05°	13.23° and 32.53°	4.31 and 24.46	Sun tracking in cold cities and without tracking in hot cities	Experimental and Mathematical		Skoplaki and Palyvos	[115]
− 20° to 90°	All cities of Saudi Arabia	24.39°	46.46°	7.44–6.22	19.28°	Experimental and computational	MATLAB	Liu and Jorden	[116]
20°–50°	Hungary	47.2°	19.1°	4800–4900 (MJ/m^2)	100° (dual-axis)	Experiment and simulation	SPSS Statistics 24 software	Analysis of variance (ANOVA)	[31]
0°–90°	Pakistan	31.5°	74.3°	2071 (annual)	− 6.5° to 61.5°	Experimental and computational	MATLAB code	Anisotropic Hay's model	[118]

Fig. 22 Optimal tilt angles for different PV modules using dual-axis tracking [31]

Description		m-Si	p-Si	a-Si	m-Si	p-Si	a-Si	m-Si	p-Si	a-Si	m-Si	p-Si	a-Si	Description
		West			South			East			Dual tracking, always optimal azimuth			
		270°			180°			90°						
Tilt angle (°) from horizontal	Dual tracking, always optimal tilt angle										100			Daily energy production compared to dual tracking (%)
	0	74	76	74	74	76	74	74	76	74				
	20	71	72	70	78	79	78	68	67	68				
	25	69	70	68	77	79	78	66	65	66				
	30	67	67	64	76	78	76	63	62	63				
	35	64	64	62	75	76	75	61	59	60				
	40	61	60	58	73	74	72	58	57	57				
	45	58	57	54	70	72	70	55	54	54				
	50	55	54	51	67	69	66	52	51	51				

100 %
79-77 %
76-74 %
73-71 %
70-68 %
67-65 %
64-62 %
61-59 %
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55-53 %
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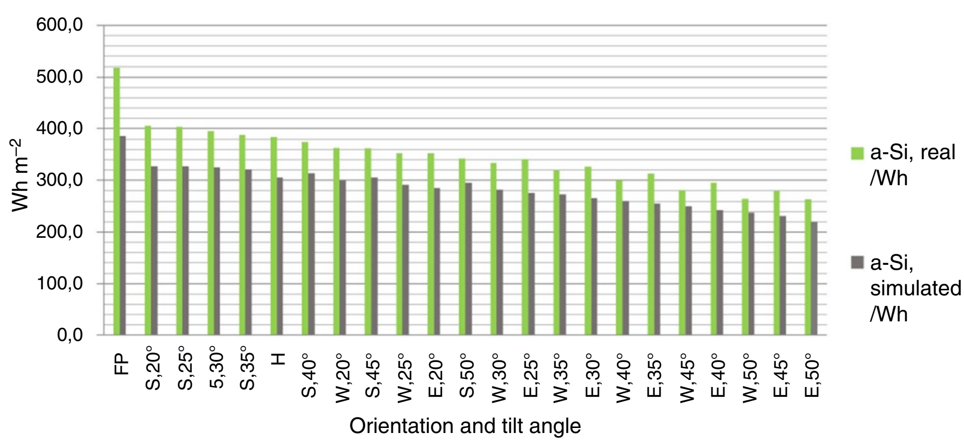

Fig. 23 Real and simulated output obtained at different tilt angles [31]

in Fig. 23. Asadullah et al. [118] modeled optimal tilt angle for Pakistan region using data from NREL. 6.6% increase in energy compared to 12 tilt angles fixed was analyzed. Using the experimental readings, the simulated readings were compared. Soiling loses were also searched out for aerosol particulates. Soiling caused 10% loss in light cases compared to 40% in heavily soiled ones. The tilt angles and soiling losses together were studied. Nearly 26.2% loss in energy was reported compared to clean panels. Figure 24 shows the performance degradation due to soiling of PV panels.

Conclusions and future scope

The review of PV panel performance affected by the variation of tilt angle is provided in this article. The location of optimum tilt angles with respect to different areas determined by the investigators is summarized here. After a careful review of articles pertinent to PV panel electricity generation and its performance affected by various operating conditions, it is found that the strategies involved are not easy to categorize them. Results of PV

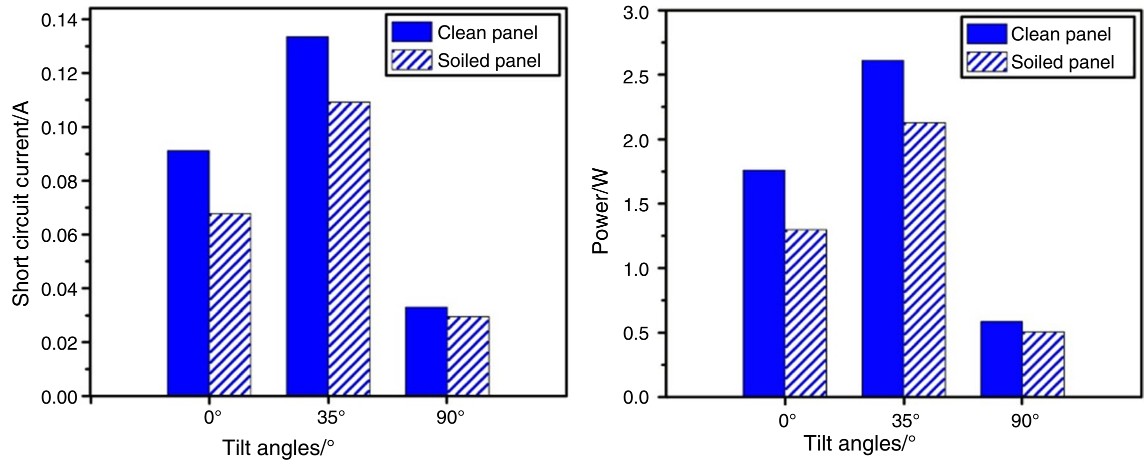

Fig. 24 Comparison of energy and current produced from soiled and clean panels [118]

system performance indicated in the past show that for a same area adopting different techniques to improve the output and minimize the cost is contrasting. Experimental procedures are found to be time-consuming and require a careful analysis. Several others lacunas noted in the PV panel performance analysis considering the effect of tilt angle are like tilt angle monthly/seasonally/annually, location, orientation, glass material, ambient temperature, etc., show a serious interrelation which cannot be considered for finding the optimum output in a single attempt, choosing any method. From the analysis, it is commonly stated that the fact is to enhance performance of sun tracking system than the manually operating system. The monthly basis optimum tilt angle is found to be more effective than the other bases but involves extra cost. Sun tracking system gives far larger electrical energy generation compared to manually or fixed tilt angle but the operating, initial, and maintenance cost are higher. The optimum tilt angles on monthly basis for some of the commonly studied countries/cities are Izmir, Turkey (0°–61°), Malaysia (− 17.16° to 29.74°), Singapore (0.11°–25°), Austria and Germany (10°–35°), India (30°–32°), Egypt (20°–30°), Saudi Arabia (8°–55°), Many locations of US (23°–40°), China (5°–10°), etc. From the vast results on optimum tilt angles using different methods, the common tilt angles obtained are as follows. The optimum tilt angles reported varies between − 17.16° and 64°, − 22.5° to 55°, 13° to 61°, − 6.5° to 100° on monthly basis when analyzed through mathematical, computational, experimental, and combination of three methods, respectively, in various cities of our planet.

Future scope

In the area of solar PV panels, the number of studies reported on single-axis tracking is seen to be challenged easily by dual-axis tracking system, but less in number. Hence, attention can be diverted on the number of works in this direction. In few cases interestingly, computational fluid dynamic analysis is also performed but the recent trend is more on combined mathematical and software approach that has to be followed for added advantage. Phase-change materials (PCM) have been used in the past to give increased output, and in future, more devotion can be given in this field. More recently, just two studies are found on the effect of combined soiling of PV panel and tilt angle on the PV panel behavior. Ambient temperature effect was considered only in a sole study performed that too computationally. But the role of ambient temperature was for sure on the performance of PV panels. Surprisingly, the use of nanofluids and tilt angle influence is not reported even in a single work. Immediate attention has to be paid in this part as nanofluids are used widely and have proved in all kinds of heat transfer-related application. It was not thought that the surface of glass cover has a role in PV panel performance, but a latest research work has proved it has. For optimization and prediction of tilt angles, use of optimization models, meta-heuristic algorithms, and design of experiments, artificial-neural fuzzy interference system can be easily and efficiently used with the available data. Finally, instead of performing different studies adopting novel methods at different locations, it is recommended to consider all the above-mentioned parameters and carry out the study globally.

References

1. Hachicha AA, Al-Sawafta I, Said Z. Impact of dust on the performance of solar photovoltaic (PV) systems under United Arab Emirates weather conditions. Renew Energy. 2019;141:287–97.
2. Afzal A, Samee ADM, Razak RKA, Ramis MK, Steady and transient state analyses on conjugate laminar forced convection heat transfer. Arch Comput Methods Eng. 2018;1–36.
3. Afzal A, Mohammed Samee AD, Abdul Razak RK, Ramis MK. Effect of spacing on thermal performance characteristics of Li-ion battery cells. J Therm Anal Calorim. 2019;135(3):1797–811.
4. Gregg A, Parker T, Swenson R. A" real world" examination of PV system design and performance. In Conference record of the thirty-first IEEE photovoltaic specialists conference; 2005.
5. Mondol JD, Yohanis YG, Norton B. Optimal sizing of array and inverter for grid-connected photovoltaic systems. Sol Energy. 2006;80(12):1517–39.
6. Tonui JK, Tripanagnostopoulos Y. Performance improvement of PV/T solar collectors with natural air flow operation. Sol Energy. 2008;82(1):1–12.
7. Mousazadeh H, Keyhani A, Javadi A, Mobli H, Abrinia K, Sharifi A. A review of principle and sun-tracking methods for maximizing solar systems output. Renew Sustain Energy Rev. 2009;13(8):1800–18.
8. Lee CY, Chou PC, Chiang CM, Lin CF. Sun tracking systems: a review. Sensors. 2009;9:3875–90.
9. Mani M, Pillai R. Impact of dust on solar photovoltaic (PV) performance: research status, challenges and recommendations. Renew Sustain Energy Rev. 2010;14(9):3124–31.
10. Chang YP. An ant direction hybrid differential evolution algorithm in determining the tilt angle for photovoltaic modules. Expert Syst Appl. 2010;37(7):5415–22.
11. Armstrong S, Hurley WG. A thermal model for photovoltaic panels under varying atmospheric conditions. Appl Therm Eng. 2010;30(11–12):1488–95.
12. Park KE, Kang GH, Kim HI, Yu GJ, Kim JT. Analysis of thermal and electrical performance of semi-transparent photovoltaic (PV) module. Energy. 2010;35(6):2681–7.
13. Seme S, Štumberger G. A novel prediction algorithm for solar angles using solar radiation and Differential Evolution for dual-axis sun tracking purposes. Sol Energy. 2011;85(11):2757–70.
14. Wang YJ, Hsu PC. An investigation on partial shading of PV modules with different connection configurations of PV cells. Energy. 2011;36(5):3069–78.
15. Beringer S, Schilke H, Lohse I, Seckmeyer G. Case study showing that the tilt angle of photovoltaic plants is nearly irrelevant. Sol Energy. 2011;85(3):470–6.
16. Zogou O, Stapountzis H. Energy analysis of an improved concept of integrated PV panels in an office building in central Greece. Appl Energy. 2011;88(3):853–66.
17. Khatib T, Mohamed A, Sopian K. Optimization of a PV/wind micro-grid for rural housing electrification using a hybrid iterative/genetic algorithm: case study of Kuala Terengganu, Malaysia. Energy Build. 2012;47:321–31.
18. Hummon M, Denholm P, Margolis R. Impact of photovoltaic orientation on its relative economic value in wholesale energy markets; 2012.
19. Khare A, Rangnekar S. A review of particle swarm optimization and its applications in solar photovoltaic system. Appl Soft Comput J. 2013;13(5):2997–3006.
20. Andrews RW, Pearce JM. The effect of spectral albedo on amorphous silicon and crystalline silicon solar photovoltaic device performance. Sol Energy. 2013;91:233–41.
21. Yadav AK, Chandel SS. Tilt angle optimization to maximize incident solar radiation: a review. Renew Sustain Energy Rev. 2013;23:503–13.
22. Kumar M, Afzal A, Ramis MK. Investigation of physicochemical and tribological properties of TiO2 nano-lubricant oil of different concentrations. Tribol Finnish J Tribol. 2017;35(3):6–15.
23. Afzal A, Mohammed Samee AD, Abdul J, Ahamed Shafvan S, Ajinas PV, Ahammedul Kabeer KM. Heat transfer analysis of plain and dimpled tubes with different spacings". Heat Transf. Res. 2018;47(3):556–68.
24. Afzal A, Samee ADM, Razak RKA. Comparative thermal performance analysis of water, engine coolant oil and MWCNT-W nanofluid in a radiator. Model Meas Control B. 2018;87(1):1–6.
25. Afzal A, Samee ADM, Razak RKA, Ramis MK. Heat transfer characteristics of MWCNT nanofluid in rectangular mini channels. Int J Heat Technol. 2018;36(1):222–8.
26. Afzal A, Mohammed Samee AD, Abdul Razak RK. Experimental thermal investigation of CuO–W nanofluid in circular minichannel. Model Meas Control B. 2017;86(2):335–44.
27. Kaplani E, Kaplanis S. Thermal modelling and experimental assessment of the dependence of PV module temperature on wind velocity and direction, module orientation and inclination. Sol Energy. 2014;107:443–60.
28. Bianchi C, Smith AD. Effects of irradiance and ambient temperature on a decision-making tool for rooftop PV array sizing for commercial buildings. In: ASME 2016 10th international conference on energy sustainability collocated with the ASME 2016 power conference and the ASME 2016 14th international conference on fuel cell science, engineering and technology. American Society of Mechanical Engineers; 2016.
29. Hsu PC, et al. Effect of switching scheme on the performance of a hybrid solar PV system. Renew Energy. 2016;96:520–30.
30. Wu Y, Wu S, Xiao L. Heat dissipation characteristics from photovoltaic cells within the partitioned or non-partitioned glazed cavity to the windy environment. Renew Energy. 2018;127:642–52.
31. Zsiborács H, et al. Change of real and simulated energy production of certain photovoltaic technologies in relation to orientation, tilt angle and dual-axis sun-tracking. A case study in Hungary. Sustain. 2018;10(5):1–19.
32. Notton G, Muselli M, Louche A. Two estimation methods for monthly mean hourly total irradiation on tilted surfaces from monthly mean daily horizontal irradiation from solar radiation data of Ajaccio, Corsica. Sol Energy. 1996;57(2):141–53.
33. Soulayman SS. On the optimum tilt of solar absorber plates. Renew Energy. 1991;1(3):551–4.
34. Krauter S. Increased electrical yield via water flow over the front of photovoltaic panels. Sol Energy Mater Sol Cells. 2004;82(1–2):131–7.
35. Royne A, Dey CJ. Design of a jet impingement cooling device for densely packed PV cells under high concentration. Sol Energy. 2007;81(8):1014–24.
36. Solanki CS, Sangani CS, Gunashekar D, Antony G. Enhanced heat dissipation of V-trough PV modules for better performance. Sol Energy Mater Sol Cells. 2008;92(12):1634–8.
37. Wang Y, Fang Z, Zhu L, Huang Q, Zhang Y, Zhang Z. The performance of silicon solar cells operated in liquids. Appl Energy. 2009;86(7–8):1037–42.
38. Maiti S, Vyas K, Ghosh PK. Performance of a silicon photovoltaic module under enhanced illumination and selective filtration of incoming radiation with simultaneous cooling. Sol Energy. 2010;84(8):1439–44.
39. Malvi CS, Dixon-Hardy DW, Crook R. Energy balance model of combined photovoltaic solar-thermal system incorporating phase change material. Sol Energy. 2011;85(7):1440–6.

40. Kim JP, Lim H, Song JH, Chang YJ, Jeon CH. Numerical analysis on the thermal characteristics of photovoltaic module with ambient temperature variation. Sol Energy Mater Sol Cells. 2011;95(1):404–7.
41. Liu L, Zhu L, Wang Y, Huang Q, Sun Y, Yin Z. Heat dissipation performance of silicon solar cells by direct dielectric liquid immersion under intensified illuminations. Sol Energy. 2011;85(5):922–30.
42. Kerzmann T, Schaefer L. System simulation of a linear concentrating photovoltaic system with an active cooling system. Renew Energy. 2012;41:254–61.
43. Teo HG, Lee PS, Hawlader MNA. An active cooling system for photovoltaic modules. Appl Energy. 2012;90(1):309–15.
44. Tina GM, Rosa-Clot M, Rosa-Clot P, Scandura PF. Optical and thermal behavior of submerged photovoltaic solar panel: SP2. Energy. 2012;39(1):17–26.
45. Rustemli S, Dincer F, Unal E, Karaaslan M, Sabah C. The analysis on sun tracking and cooling systems for photovoltaic panels. Renew Sustain Energy Rev. 2013;22:598–603.
46. Kahoul N, Houabes M, Sadok M. Assessing the early degradation of photovoltaic modules performance in the Saharan region. Energy Convers Manag. 2014;82:320–6.
47. Karami N, Rahimi M. Heat transfer enhancement in a hybrid microchannel-photovoltaic cell using Boehmite nanofluid. Int Commun Heat Mass Transf. 2014;55:45–52.
48. Nižetić S, Arıcı M, Bilgin F, Grubišić-Čabo F. Investigation of pork fat as potential novel phase change material for passive cooling applications in photovoltaics. J Clean Prod. 2018;170:1006–16.
49. Arıcı M, Bilgin F, Nižetić S, Papadopoulos AM. Phase change material based cooling of photovoltaic panel: a simplified numerical model for the optimization of the phase change material layer and general economic evaluation. J Clean Prod. 2018;189:738–45.
50. Pepelyshev A, Steland A, Avellan-Hampe A. Acceptance sampling plans for photovoltaic modules with two-sided specification limits. Prog Photovolt Res Appl. 2014;22(6):603–11.
51. Karami N, Rahimi M. Heat transfer enhancement in a PV cell using Boehmite nanofluid. Energy Convers Manag. 2014;86:275–85.
52. Wu S, Xiong C. Passive cooling technology for photovoltaic panels for domestic houses. Int J Low-Carbon Technol. 2014;9(2):118–26.
53. Irwan YM, et al. Indoor test performance of PV panel through water cooling method, vol. 79. Hoboken: Elsevier; 2015.
54. Rahman MM, Hasanuzzaman M, Rahim NA. Effects of various parameters on PV-module power and efficiency. Energy Convers Manag. 2015;103:348–58.
55. Sahay A, Sethi VK, Tiwari AC, Pandey M. A review of solar photovoltaic panel cooling systems with special reference to Ground coupled central panel cooling system (GC-CPCS). Renew Sustain Energy Rev. 2015;42:306–12.
56. Hasanuzzaman M, Malek ABMA, Islam MM, Pandey AK, Rahim NA. Global advancement of cooling technologies for PV systems: a review. Sol Energy. 2016;137:25–45.
57. Liu B, Jordan R. Daily insolation on surfaces tilted towards equator. ASHRAE J. 1961;10.
58. Tsalides P, Thanailakis A. Direct computation of the array optimum tilt angle in constant-tilt photovoltaic systems. Sol Cells. 1985;14(1):83–94.
59. Yakup MAHM, Malik AQ. AQ Malik (2001) Optimum tilt angle and orientation for solar collector in Brunei Darussalam. Renew. Energy. 2001;24(9):223–34.
60. Ulgen K. Optimum tilt angle for solar collectors. Energy Sources Part A Recover Util Environ Effic. 2006;28(13):1171–80.
61. Gunerhan H, Hepbasli A. Determination of the optimum tilt angle of solar collectors for building applications. Build Environ. 2007;42(2):779–83.
62. Chang TP. Study on the optimal tilt angle of solar collector according to different radiation types. Int J Appl Sci Eng. 2008;6(2):151–61.
63. Zhao Q, Wang P, Goel L. Optimal PV panel tilt angle based on solar radiation prediction. In: 2010 IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems (PMAPS 2010) 2010; pp 425–430.
64. Tang R, Gao W, Yu Y, Chen H. Optimal tilt-angles of all-glass evacuated tube solar collectors. Energy. 2009;34(9):1387–95.
65. Daut I, Irwanto M, Irwan YM, Gomesh N, Ahmad NS. Clear sky global solar irradiance on tilt angles of photovoltaic module in Perlis, Northern Malaysia. In: INECCE 2011: the 1st international conference on electrical, control and computer engineering, 2011; pp 445–450.
66. Pour HSS, Beheshti HK, Rahnama M. The gain of the energy under the optimum angles of solar panels during a year in Isfahan, Iran. Energy Sources Part A Recover Util Environ Effic. 2011;33(13):1281–90.
67. Elhab BR, et al. Optimizing tilt angles and orientations of solar panels for Kuala Lumpur, Malaysia. Sci Res Essays. 2012;7(42):3758–67.
68. Sunderan P, Ismail A, Singh B. Optimum tilt angle and orientation of stand-alone photovoltaic electricity generation systems for rural electrification. J Appl Sci. 2011;11(7):1219–24.
69. T. Khatib, A. Mohamed, and K. Sopian, "On the monthly optimum tilt angle of solar panel for five sites in Malaysia. In: 2012 IEEE international power engineering and optimization conference (PEOCO) 2012—conference Proceedings., no. June, 2012; pp. 7–10.
70. Agarwal A, Vashishtha VK, Mishra SN. Comparative approach for the optimization of tilt angle to receive maximum radiation. Int J Eng Res Technol. 2012;1(5):1–9.
71. Sun L, Lu L, Yang H. Optimum design of shading-type building-integrated photovoltaic claddings with different surface azimuth angles. Appl Energy. 2012;90(1):233–40.
72. Khorasanizadeh H, Mohammadi K, Mostafaeipour A. Establishing a diffuse solar radiation model for determining the optimum tilt angle of solar surfaces in Tabass, Iran. Energy Convers Manag. 2014;78:805–14.
73. Drury E, Lopez A, Denholm P, Margolis R. Relative performance of tracking versus fi xed tilt photovoltaic systems in the USA. Prog Photovoltaics Res Appl. 2014;22:1302–15.
74. Khoo YS, Reindl T, Aberle AG, Member S. Optimal orientation and tilt angle for maximizing in-plane solar irradiation for PV applications in Singapore. IEEE J Photovolt. 2014;4(2):647–53.
75. Hartner M, Ortner A, Hiesl A, Haas R. East to west—the optimal tilt angle and orientation of photovoltaic panels from an electricity system perspective. Appl Energy. 2015;160:94–107.
76. Despotovic M, Nedic V. Comparison of optimum tilt angles of solar collectors determined at yearly, seasonal and monthly levels. Energy Convers Manag. 2015;97:121–31.
77. Farhan S, Tabbassum K, Talpur S, Bux M. Evaluation of solar energy resources by establishing empirical models for diffuse solar radiation on tilted surface and analysis for optimum tilt angle for a prospective location in southern region of Sindh, Pakistan. Int J Electr Power Energy Syst. 2015;64:1073–80.
78. Soulayman S, Sabbagh W. Solar collector optimum tilt and orientation. Open J Renew Sustain Energy. 2015;2(1):1–9.
79. Nijegorodov N, Devan KRS, Jain PK, Carlsson S. Atmospheric transmittance models and an of absorber plate, variously oriented at any latitude. Renew Energy. 1994;4(5):529–43.

80. Calabrò E. An algorithm to determine the optimum tilt angle of. J Renew Energy. 2013;2013:12.
81. Akhlaghi S, Sangrody H, Sarailoo M, Rezaeiahari M. Efficient operation of residential solar panels with determination of the optimal tilt angle and optimal intervals based on forecasting model. IET Renew Power Gener. 2017;11:1261–7.
82. Tripathy M, Yadav S, Sadhu PK, Panda SK. Determination of optimum tilt angle and accurate insolation of BIPV panel influenced by adverse effect of shadow. Renew Energy. 2017;104:211–23.
83. Yadav S, Panda SK, Tripathy M. Performance of building integrated photovoltaic thermal system with PV module installed at optimum tilt angle and influenced by shadow. Renew Energy. 2018;127:11–23.
84. Conceição R, Silva HG, Fialho L, Lopes FM, Collares-Pereira M. PV system design with the effect of soiling on the optimum tilt angle. Renew Energy. 2019;133:787–96.
85. Shariah A, Al-Akhras MA, Al-Omari IA. Optimizing the tilt angle of solar collectors. Renew Energy. 2002;26:587–98.
86. Hussein HMS, Ahmad GE, El-Ghetany HH. Performance evaluation of photovoltaic modules at different tilt angles and orientations. Energy Convers Manag. 2004;45(15–16):2441–52.
87. Calabrò E. Determining optimum tilt angles of photovoltaic panels at typical north-tropical latitudes. J Renew Sustain Energy. 2009;1(3):033104.
88. Benghanem M. Optimization of tilt angle for solar panel: case study for Madinah, Saudi Arabia. Appl Energy. 2011;88(4):1427–33.
89. Ahmad MJ, Tiwari GN. Optimization of tilt angle for solar collector to receive maximum radiation. Open Renew Energy J. 2009;2:19–24.
90. Rowlands IH, Kemery BP, Beausoleil-Morrison I. Optimal solar-PV tilt angle and azimuth: an Ontario (Canada) case-study. Energy Policy. 2011;39(3):1397–409.
91. Bojić M, Bigot D, Miranville F, Parvedy-Patou A, Radulović J. Optimizing performances of photovoltaics in Reunion Island—tilt angle. Prog Photovolt Res Appl. 2011;20(8):923–35.
92. Emam M, Ookawara S, Ahmed M. Performance study and analysis of an inclined concentrated photovoltaic-phase change material system. Sol Energy. 2017;150:229–45.
93. Rhodes JD, Upshaw CR, Cole WJ, Holcomb CL, Webber ME. A multi-objective assessment of the effect of solar PV array orientation and tilt on energy production and system economics. Sol Energy. 2014;108:28–40.
94. Gharakhani Siraki A, Pillay P. Study of optimum tilt angles for solar panels in different latitudes for urban applications. Sol Energy. 2012;86(6):1920–8.
95. Duffie J, Beckman W. Solar engineering of thermal processes. 3rd ed. New York: Wiley; 1980.
96. Vargas O, Pinilla G, Vasquez J. Sizing and study of the energy production of a grid—tied photovoltaic system using PV syst software. TECCIENCIA. 2017;12(22):27–32.
97. Khanna S, Reddy KS, Mallick TK. Performance analysis of tilted photovoltaic system integrated with phase change material under varying operating conditions. Energy. 2017;133:887–99.
98. Lu H, Zhao W. Effects of particle sizes and tilt angles on dust deposition characteristics of a ground-mounted solar photovoltaic system. Appl Energy. 2018;220(2018):514–26.
99. Lau KY, Tan CW, Yatim AHM. Effects of ambient temperatures, tilt angles, and orientations on hybrid photovoltaic/diesel systems under equatorial climates. Renew Sustain Energy Rev. 2018;81(June):2625–36.
100. Ali Morad AM, Al-Sayyab AKS, Abdulwahid MA. Optimisation of tilted angles of a photovoltaic cell to determine the maximum generated electric power: a case study of some Iraqi cities. Case Stud Therm Eng. 2018;12:484–8.
101. Jacobson MZ, Jadhav V. World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels. Sol Energy. 2017;169:55–66.
102. Kumar NM, Dinniyah FS. Influence of tilt angle on energy yields and performance ratios of grid connected photovoltaic generators in Southeast Asia. Prog Ind Ecol Int J. 2019;13(3):264.
103. Al Garni HZ, Awasthi A, Wright D. Optimal orientation angles for maximizing energy yield for solar PV in Saudi Arabia. Renew Energy. 2019;133:538–50.
104. Asl-Soleimani E, Farhangi S, Zabihi MS. The effect of tilt angle, air pollution on performance of photovoltaic systems in Tehran. Renew Energy. 2001;24(3–4):459–68.
105. Kacira M, Simsek M, Babur Y, Demirkol S. Determining optimum tilt angles and orientations of photovoltaic panels in Sanliurfa, Turkey. Renew Energy. 2004;29(8):1265–75.
106. Elhassan ZAM, Zain MFM, Sopian K, Awadalla A. Output energy of photovoltaic module directed at optimum slope angle in Kuala Lumpur, Malaysia. Res J Appl Sci. 2011;6(2):104–9.
107. Xu R, Ni K, Hu Y, Si J, Wen H, Yu D. Analysis of the optimum tilt angle for a soiled PV panel. Energy Convers Manag. 2017;148:100–9.
108. Fahl P, Ganapathisubbu SG. Tracking benefits for solar collectors installed in Bangalore. J Renew Sustain Energy. 2011;3(2):1–12.
109. Sun LL, Li M, Yuan YP, Cao XL, Lei B, Yu NY. Effect of tilt angle and connection mode of PVT modules on the energy efficiency of a hot water system for high-rise residential buildings. Renew Energy. 2016;93:291–301.
110. Abdeen E, Orabi M, Hasaneen E. Optimum tilt angle for photovoltaic system in desert environment. Sol Energy. 2017;155:267–80.
111. Zhi Zhang L, Jian Pan A, Rong Cai R, Lu H. Indoor experiments of dust deposition reduction on solar cell covering glass by transparent super-hydrophobic coating with different tilt angles. Sol Energy. 2019;188:1146–55.
112. Asowata O, Swart J, Pienaar C. Optimum tilt angles for photovoltaic panels during winter months in the vaal triangle, South Africa. Smart Grid Renew. Energy. 2012;03(02):119–25.
113. Liu X. Calculation and analysis of optimal tilt angle for PV/T hybrid collector. In: Proceedings of the 2012 international conference on intelligent system design and engineering application (ISDEA) 2012; pp. 791–795.
114. Kaldellis J, Zafirakis D. Experimental investigation of the optimum photovoltaic panels' tilt angle during the summer period. Energy. 2012;38(1):305–14.
115. Eldin SAS, Abd-elhady MS, Kandil HA. Feasibility of solar tracking systems for PV panels in hot and cold regions. Renew Energy. 2016;85:228–33.
116. Kaddoura TO, Ramli MAM, Al-turki YA. On the estimation of the optimum tilt angle of PV panel in Saudi Arabia. Renew Sustain Energy Rev. 2016;65:626–34.
117. Malek NAAA, Chew JM, Naamandadin NA. A study on association between tilt angle, solar insolation exposure and output of solar PV panel using BIM 3D modelling. In: MATEC web of conferences (ICRMCE 2018), 2018; vol. 195, 06009, p. 11.
118. Ullah A, Imran H, Maqsood Z, Butt NZ. Investigation of optimal tilt angles and effects of soiling on PV energy production in Pakistan. Renew Energy. 2019;139:830–43.