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Determination of Optimum Tilt Angle for Different Photovoltaic Technologies Considering Ambient Conditions: A Case Study for Burdur, Turkey

This study presents a numerical approach to calculate the optimum photovoltaic (PV) tilt angle by considering the three different PV technologies (monocrystalline, polycrystalline, and thin film). This analysis focuses on determination of optimum tilt angle considering seasonal and yearly solar radiation on a plane (Wh/m^2) and seasonal and yearly energy production (Wh) of PVs. The angle at maximum global radiation and maximum energy output is considered as the optimum tilt angle. It is found that optimum tilt angles obtained by total radiation and total energy output are different from each other considering seasonal and yearly base. Total radiation-based tilt angle results show that the optimum tilt angle is 13 deg in spring, 9 deg in summer, 17 deg in autumn, 12 deg in winter, and 12 deg as yearly. Energy production-based optimum tilt angles vary from 5 deg to 13 deg for monocrystalline, from 11 deg to 15 deg for polycrystalline, and from 12 deg to 25 deg for thin film technology according to seasonal and yearly tilt angle results.
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1 Introduction

Renewable energy resources' utilization has been rapidly increasing for the last 20 years because of depleting fossil-based fuels and environmental awareness [1]. Especially, the photovoltaic (PV) solar energy system-based energy generation has begun to be used often in order to meet the energy demand [2].

For the design and development of solar energy systems, the amount of radiation falling over PV panel and radiation changes are required to be known. As measured solar radiation data are not available for many places, the radiation is required to be estimated [3]. For the radiation estimation concerning horizontal plane, different techniques are used [4–6]. The radiation falling over the PV system is mainly affected from PV system orientation and tilt angle [7,8]. The PV panels are generally placed toward equator. This means that they will be placed toward south at northern hemisphere and toward north at southern hemisphere. The radiation changes depending on meteorological conditions affect optimum tilt angles of the PVs for the different regions.

The maximum daily energy production can be obtained by using the solar tracking systems that are constituted from mechanic equipment and continuously follow the direction of the sun [9]. But some aspects regarding to these tracking systems such as being expensive, consuming energy for their operation, and having hard operation-maintenance procedures decrease its practicability. Therefore, placing PV systems at fixed optimum tilt angle is the easy and most practical way. For determination of optimum tilt angle, there are different studies. Some of these studies presented an approach in terms of quality and quantity [10–13], and some of them presented analytical solutions [14–17]. The optimum tilt angle may change locally, and the studies carried out in this way are generally local scaled [18–27].

For optimum design of PV systems, it is prior to determine system performance at the site of application. The amount of power produced by PV system depends upon the solar radiation, tilt angle, azimuth angle, and environmental effects [28]. In order to predict the energy generation of photovoltaic (PV) modules, it is required to predict the module temperature as a function of ambient temperature, wind speed, and solar radiation [29]. Performance of PV technologies depends on site-specific weather parameters. For the accurate evaluation of performance of PVs, site-specific parameters are needed to be used [30]. Especially, PV surface and cell temperature affect the PV performance. A study conducted in Ref. [31] shows that when the ambient temperature is 1.5–3 °C decreased, mean output power increases about 1%. Additionally, different PV technologies have different performances due to the variations in spectral response, the different temperature coefficients, and thermal annealing [32].

In this study, an improved numerical methodology is proposed to determine the optimum tilt angle of three PV technologies. Optimum tilt angles of photovoltaic (PV) panels produced by different technologies are calculated by seasonal total radiation on tilted surface, yearly total solar radiation on tilted surface, and seasonal and yearly energy production of PVs. Output power of PVs is obtained by PV model which accuracy was tested in previous study. The meteorological data of Burdur—the location of the study—such as solar radiation, ambient temperature, and wind speed are taken into account in the model for each PV technology. The numerical background and methodology of this study is described in Sec. 2. Simulation results are discussed in Sec. 3, and this paper concluded with Sec. 4.

2 Numerical Background and Methodology

The global radiation on tilted surface is calculated by using extraterrestrial radiation, global radiation on horizontal surface,

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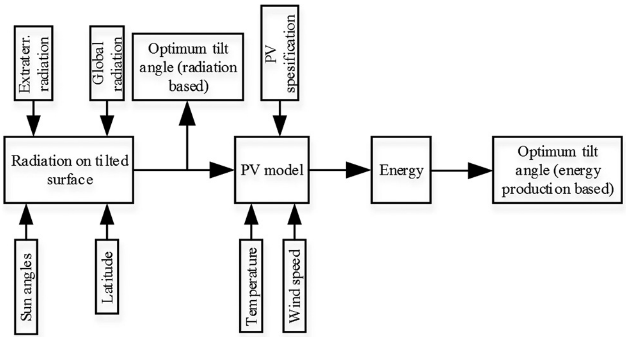

Fig. 1 The block diagram of the methodology

Fig. 2 Measurement setup for global radiation on horizontal and tilted surfaces

sun angles, and latitude [33]. The calculation method is also verified with comparison of measured and calculated data. The optimum tilt angle of Burdur, Turkey is determined considering seasonal and yearly total radiation on a tilted surface. Then, the MATLAB/SIMULINK models of PV technologies are developed to obtain energy output of PVs. In the PV model, the radiation on tilted surface, ambient temperature, wind speed, and PV specifications are the input parameters, and PV voltage and PV current are the output parameters. Total energy output of PVs is calculated for different tilt angles. Therefore, yearly and seasonal optimum tilt angles of different PV technologies are determined for Burdur, Turkey considering the seasonal and yearly energy production of PVs. The block diagram of methodology is given in Fig. 1.

2.1 Optimum Tilt Angle Determination Model. Two different cases are considered for determination of optimum tilt angle. First case is to maximize radiation on a square meter area for optimum tilt angle. Equation (6) is used for this case depending on maximization function in the following equation:

$$\max[I_T(I_{ex}, I_G, \varphi, \beta, \delta, h, \rho)] \tag{1}$$

Second case is to maximize energy production of PVs for optimum tilt angle determination. Energy production of PV in Eq. (3) is used for this case considering maximization function in Eq. (2)

$$\max[E_{\mathrm{pv}}(I_T, T, w, V_{\mathrm{pv}}, I_{\mathrm{pv}})] \tag{2}$$

$$E_{\mathrm{pv}} = (V_{\mathrm{pv}} \cdot I_{\mathrm{pv}}) \cdot t \tag{3}$$

Equations (2) and (3) are obtained by PV model created in MATLAB/SIMULINK. The tilt angle constraint in Eq. (4) was taken into account for both first and second cases

$$0 < \beta < 90 \tag{4}$$

2.2 Solar Radiation on a Tilted Surface. The incident radiation to horizontal surface depends on the distance between earth and sun, latitude and longitude of the location, sun angles, water vapor, dust particles, etc. Therefore, all these factors should be taken into account in mathematical equation which is used to obtain radiation on tilted surface.

The radiation on horizontal and tilted surfaces (41 deg) is measured with two different pyranometers. Measurement setup is given in Fig. 2. First, the radiation on horizontal surface must be separated to direct radiation and diffused radiation components for calculating radiation on tilted surface by using global radiation [33]. The total radiation at 41 deg is calculated with direct and diffused components of the radiation on horizontal surface and other parameters (sun angles, latitude, etc.). The mathematical equations for calculation of radiation on tilted surface are given below [34]

$$R_B = \frac{\cos(\varphi-\beta)\cdot\cos(\delta)\cdot\cos(h) + \sin(\varphi-\beta)\cdot\sin(\delta)}{\cos(\varphi)\cdot\cos(\delta)\cdot\cos(h) + \sin(\varphi)\cdot\sin(\delta)} \tag{5}$$

$$I_T = I_B \cdot R_B + I_D \cdot \left(\frac{1+\cos(\beta)}{2}\right) + I_G \cdot \rho \cdot \left(\frac{1-\cos(\beta)}{2}\right) \tag{6}$$

where R_B is the ratio between beam radiation on horizontal and tilted surfaces. The total radiation on tilted surface consists of beam, diffused, and reflected radiations [35]. Diffused radiation on tilted surface is proportional to amount of sky seen by the tilted surface. However, reflected radiation on tilted surface is proportional to amount of ground seen by the tilted surface and ground albedo [28].

Calculated radiation on tilted surface is compared with measured radiation which is provided from second pyranometer positioned at the same angle (41 deg) in real environmental conditions. Measured and calculated radiations on tilted surface (41 deg) are given in Fig. 3. The radiation result from the calculation covers the measured radiation under variable radiation condition.

2.3 PV Model. Reference [34] is taken into account to create PV model. Simplified equivalent circuit in PV model is shown in Fig. 4. PV current is calculated as a function of voltage in this model. The parameters in PV panel's datasheet are used for PV

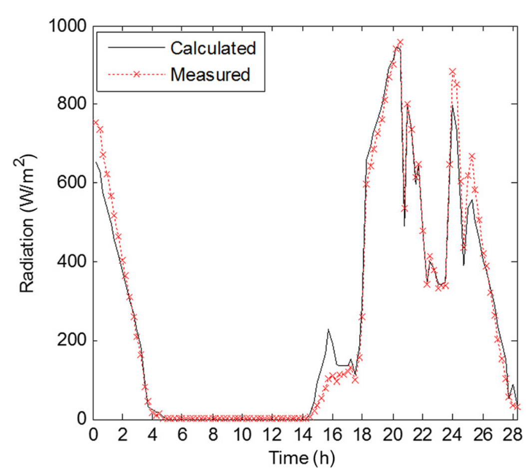

Fig. 3 Comparison of calculated and measured radiations on tilted surface

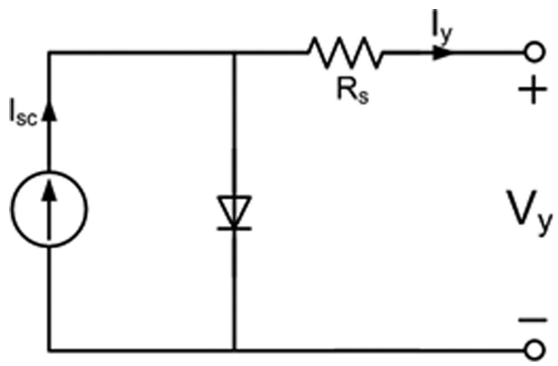

Fig. 4 Simplified equivalent circuit model

specifications. The radiation, the ambient temperature, and the wind speed are used as input parameters. PV current and PV voltage are output parameters in this model.

In this study, three different PV technologies (monocrystalline, polycrystalline, and thin film) are used to determine optimum tilt angle. The junction temperature is calculated as a function of ambient temperature, radiation, wind speed, and PV technology [29,33,34,36]. The cell temperature is given in the following equation:

$$T_C = 1,14 \cdot (T - T_S) + 0,0175 \cdot (I_T - 300) - k_r \cdot w + 30 \quad (7)$$

Here, k_r is a coefficient which varies for each PV technology. k_r is 1509 for monocrystalline and 1468 for polycrystalline, while it is 1450 for thin film technology [29]. The specifications of PV panels used in this study are given in Table 1.

The measured power value of PV panels under ambient conditions is compared with power value obtained from PV model for each PV technology. It was seen that PV models with monocrystalline, polycrystalline, and thin film technologies are carried out with 3.25%, 13.93%, and 3.70% error compared to measured values, respectively [34].

The maximum power obtained from PV panels varies depending on radiation, ambient temperature, and wind speed. PV panels in a solar power plant should be operated at maximum power point consistently. P&O algorithm is used for maximum power point tracking in the models [37,38]. The MATLAB/SIMULINK block diagram of PV model is given in Fig. 5.

The optimum tilt angle in Burdur, Turkey is calculated by radiation, ambient temperature, and wind speed values which are given in Fig. 6.

3 Simulation Results and Discussion

Radiation-based PV optimum tilt angles are obtained, which run in a verified radiation model given in Sec. 2.2, as seasonal and annual by using Burdur's radiation data of 2006. Seasonal total radiation on a square meter area is given in Fig. 7 for different tilt angles.

As can be clearly seen in Fig. 6, the total radiation reached the highest value for all tilt angles in summer. In contrast, the total radiation value reached the minimum value in winter which is almost equal to one third of total radiation in summer. Also, the total radiation in spring is higher than the total radiation in autumn for all tilt angles. Considering the total radiation, optimum tilt angles for spring, summer, autumn, and winter are calculated as 13 deg, 9 deg, 17 deg, and 12 deg, respectively. The annual optimum tilt angle is found to be 12 deg when the total annual radiation is calculated in a square meter area for all tilt angles. The annual total radiation according to different tilt angles is given in Fig. 8.

Although the total radiation in a square meter area reaches to the highest value in summer (9 deg) considering the seasonal

Table 1 Characteristic values of PV panels

Quantity	Monocrystalline	Polycrystalline	Thin film
Peak power (W)	50	60	55
Number of cell	36	36	—
Short circuit current (A)	3.14	3.97	1.57
Open circuit voltage (V)	21.4	31.7	61.4
Maximum power current (A)	2.88	3.41	1.21
Maximum power voltage (V)	17.4	17.6	45.45
Dimension (mm)	629 × 535 × 28	755 × 666 × 48	1397 × 635 × 6
Current temperature coefficient (%/°C)	0.05	0.055	0.09
Voltage temperature coefficient (%/°C)	−0.34	−0.33	−0.33
Weight (kg)	4.3	5.1	16

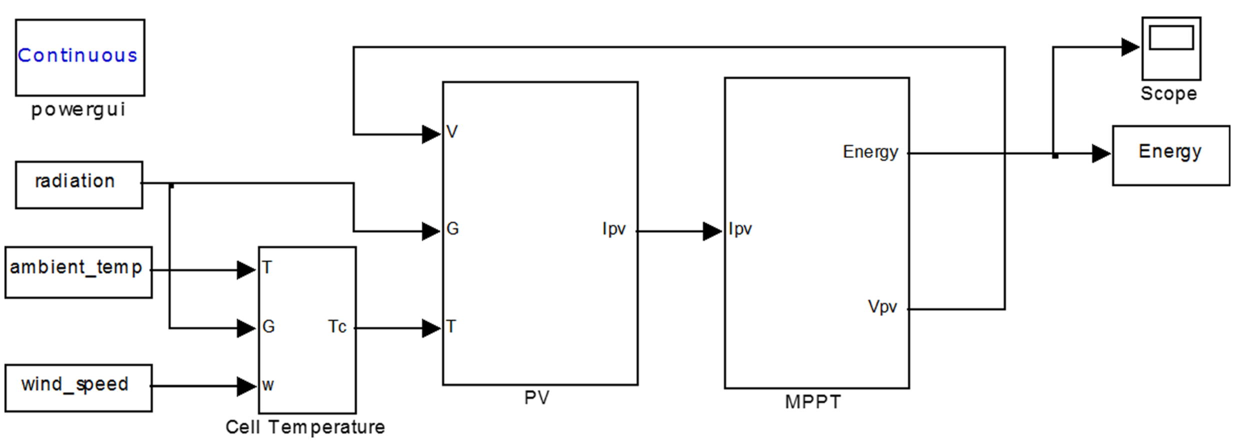

Fig. 5 MATLAB/SIMULINK block diagram of PV panel

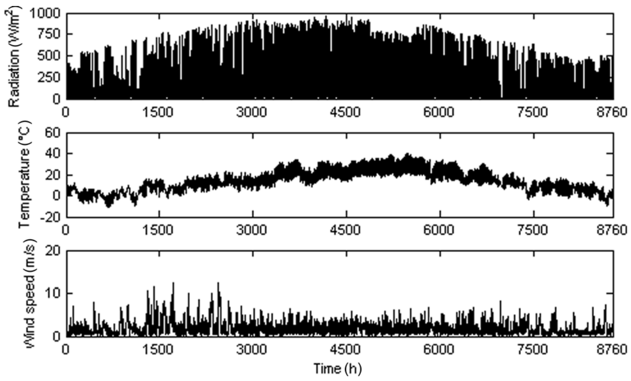

Fig. 6 The radiation, ambient temperature, and wind speed values for Burdur

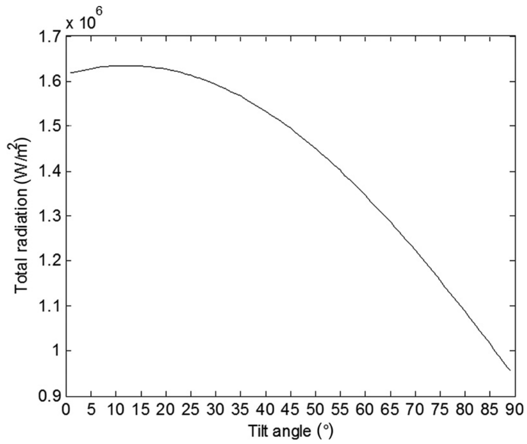

Fig. 8 The annual total radiation on a tilted surface

results, the annual optimum tilt angle equals to the optimum tilt angle in winter (12 deg). Thus, other seasons should be considered as well as summer, where total solar radiation reaches the highest value, for radiation-based optimum tilt angle determination. Seasonal and yearly optimum tilt angles based on total radiation are given in Table 2.

Three different PV technologies (Table 1) are modeled in MATLAB/SIMULINK with using equivalent circuit given in Fig. 4. The block diagram of PV model is given in Fig. 5. Seasonal energy outputs of three different technologies are presented in Fig. 9 for different tilt angles. It is clear from the seasonal energy output that optimum tilt angles of PV panels are different from each other. Especially in summer and autumn, because of the ambient temperature is reached the highest values, the obtained optimum tilt angle of each PV technology is different. PV energy output reached the maximum value in spring for polycrystalline and monocrystalline technologies and in summer for thin film technology. Thus, output power of thin film technology increases if subject to high temperature. It is seen that the ambient temperature has a significant impact on PV technologies. However, the optimum tilt angles' values that obtained for winter and spring are close to each other. Seasonal optimum tilt angles of different PV technologies are given in Table 3.

When the radiation, temperature, and wind speed variations in Fig. 6 are examined, it is seen that the radiation and the temperature get at their maximum value in summer. However, the highest wind speed occurs in the spring. Although high radiation in summer increases PV energy production, high temperature and low wind speed decrease energy production lower than PV power production in spring. The results show that not only radiation but also wind speed and temperature have an important role on PV power generation.

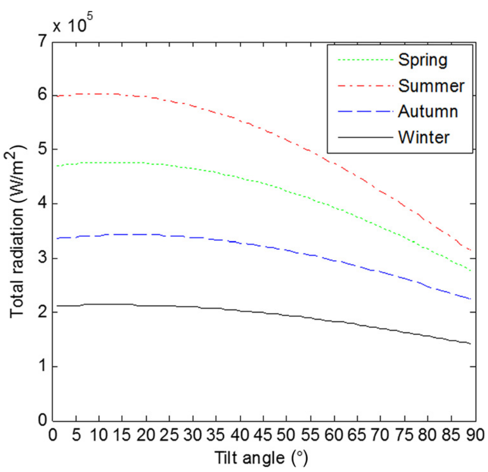

Fig. 7 Total radiation on a square meter area for different tilted surfaces

Table 2 Optimum tilt angle based on total radiation

Season	Spring	Summer	Autumn	Winter	Yearly
Optimum tilt angle (deg)	13	9	17	12	12

The annual energy productions according to the tilt angles for different PV technologies are shown in Fig. 10. Annual optimum tilt angles are calculated as 13 deg, 11 deg, and 12 deg for monocrystalline, polycrystalline, and thin film technologies, respectively. Annual optimum tilt angles are close to each other. Moreover, the oscillations of seasonal (Fig. 9) and annual (Fig. 10) energy production of thin film PV technology is higher than the both of monocrystalline and polycrystalline PV technologies. It is clear from the aforementioned result that thin film PV technology is seen to be most affected by tilt angle change. Optimum tilt angles are given in Table 3 according to seasonal and annual energy production.

Radiation and energy production-based annual optimum tilt angles are close to each other for monocrystalline and polycrystalline technologies and even the same for thin film technology. However, when calculated seasonal tilt angles are examined, it is seen that the results are almost the similar values for only in winter but optimum tilt angles are different to each other for the other seasons. Especially in the summer and autumn, radiation-based optimum tilt angles are quite different compared to energy production-based optimum tilt angles.

4 Conclusion

In this study, seasonal and yearly optimum tilt angles for three PV technologies are determined based on total radiation on a plane and energy production considering temperature and solar radiation wind speed for Burdur, Turkey. Maximizing the total solar radiation on a plane is not sufficient criteria for determination of optimum tilt angle. Because different PV technologies have different performances due to the variations in spectral response, the different temperature coefficients, and thermal annealing. Therefore, the cell temperature and the wind speed which affect the output power of PVs are also taken into account for energy output-based optimum tilt angle determination. Furthermore, seasonal and yearly optimum tilt angles are different for three used PV technologies. It is clear from the radiation or energy output-based results that utilizing same tilt angle for different PV technologies result in different performances. PV plant designer

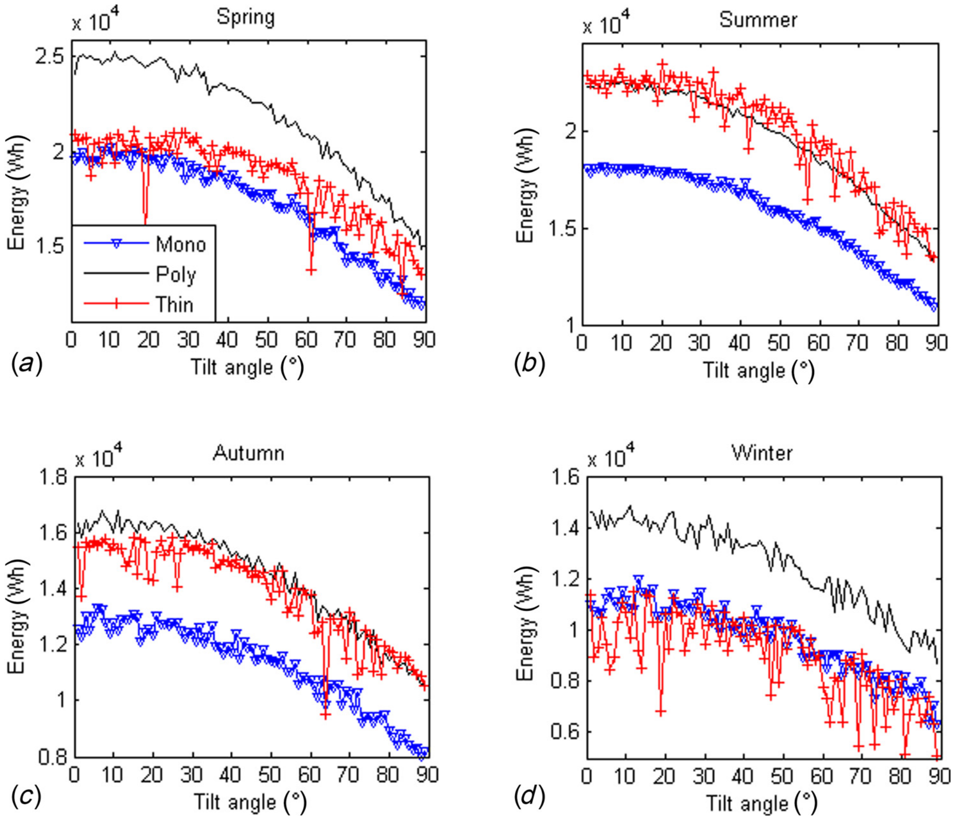

Fig. 9 Seasonal energy production of PV technologies

Table 3 Optimum tilt angle based on energy production

PV technology	Spring (deg)	Summer (deg)	Autumn (deg)	Winter (deg)	Yearly (deg)
Monocrystalline	10	5	6	13	13
Polycrystalline	11	15	11	11	11
Thin film	16	20	25	12	12

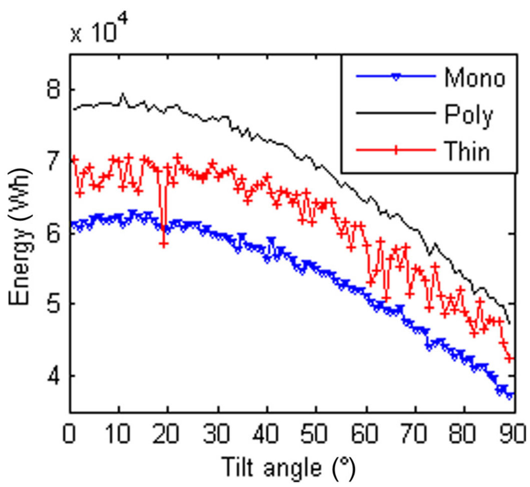

Fig. 10 Annual energy production of PV technologies

should be considered the site-specific performance of PV technologies.

The methodology of this study is a mathematical model so it can be applied for different regions in the world where radiation, temperature, and wind speed datum are available. Thus, seasonal and yearly optimum tilt angles can be calculated for different PV technologies. Also, the optimum tilt angle can be determined daily and monthly. As a future study, optimum tilt angle results should be compared with actual PV plant performance considering the economical parameters.

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Nomenclature

E_{pv} = PV energy, Wh
h = hour angle, deg
I_B = beam radiation on horizontal surface, W/m^2
I_D = diffused radiation on horizontal surface, W/m^2
I_{ex} = extraterrestrial radiation, W/m^2
I_G = global radiation, W/m^2
I_{pv} = PV current, A
I_T = radiation on tilted surface, W/m^2
k_r = wind speed coefficient
R_B = ratio of beam radiation
t = time, h
T = ambient temperature, °C

T_C = PV cell temperature, °C
T_S = temperature under standard conditions, °C
V_{pv} = PV voltage, V
w = wind speed, m/s
β = tilt angle, deg
δ = declination angle, deg
ρ = reflection coefficient
φ = latitude, deg

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