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Research Article

Impact of Climatic Conditions on PV Array's Optimum Tilt Angle

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Abstract

One of the most important parameters in order to obtain maximum solar radiation for solar power system is the optimum tilt angle of photovoltaic (PV) panels. In this article, the optimum tilt angles of photovoltaic panels are determined for regions of different climatic zones. The annual maximum energy output of PV panels is calculated in MATLAB considering irradiance data only. Annual, seasonal and monthly optimum tilt angles of PV arrays of approximately same latitude with different climatic zones are calculated for fixed tilt angles on the basis of maximum energy output. The incident global solar radiation on the horizontal surface is separated to its direct and diffuse components with a solar angle based mathematical model. Depending on region's latitudes, direct and diffuse radiation, and tilt angle of PV panels, the incident global radiation on inclined surface is calculated for USA conditions. This study is conducted for seven different regions with very close latitudes but different climate zones. It is clear from the result that PV panels with fixed tilt angles located in approximately-same latitudes may result in different optimum tilt angle due to the dissimilar climatic impacts.

Keywords: PV Array, optimum tilt angle, climatic condition

İklim Koşullarının PV Panel Optimum Eğim Açısına Etkisi

Öz

PV panel yüzeyine maksimum ışınımın düşmesi için en önemli parametrelerden bir tanesi optimum eğim açısıdır. Bu çalışmada, farklı iklim bölgelerindeki PV paneller için optimum eğim açısı belirlenmiştir. PV panellerin yıllık enerji üretim değerleri MATLAB ara yüz programı yardımı sadece ışınım verisi kullanılarak hesaplanmıştır. Farklı iklim koşullarında ve yaklaşık aynı enlemde sabit konumlandırılmışmış PV panellerin yıllık, mevsimlik ve aylık maksimum enerji üretiminin sağlandığı optimum eğim açıları hesaplanmıştır. Optimum eğim açısı hesabı için öncelikle yatay yüzeydeki toplam ışınım, güneş açılarına göre matematiksel modeller kullanılarak direk ve yayınık bileşenlerine ayrılmıştır. Enlem açısı, yatay düzlemdeki direk ve yayınık ışınım bileşenleri ve eğim açısına göre eğimli yüzeydeki ışınım miktarı ABD koşulları için hesaplanmıştır. Bu adımlar, enlemleri birbirine çok yakın fakat farklı iklim koşullarındaki yedi bölge için tekrarlanmıştır. Sonuç olarak, yaklaşık olarak aynı enlemlerde bulunan sabit eğim açılı PV paneller, farklı iklimsel etkilere bağlı olarak farklı optimum eğim açısıyla konumlandırılması gerektiği görülmüştür.

Anahtar kelimeler: PV panel, optimum eğim açısı, iklim koşulları

1. Introduction

The solar energy is proved to be one of the foremost renewable energy resources in areas having great deal of solar potential. The popularity of PV systems have been increasing every day because of its applicability to different areas, low M&O cost and long lifetime, and particularly environmental advantages. Due to high initial investment cost of PV system, it is necessary to operate the PV panels with possible highest energy output. This necessity is dependent upon the factors such as radiation amount on PV surface and weather temperature (Li et al, 2011; Ishaque et al, 2012). While temperature rise of PV panels reduce the performance outcome, radiation change affects the system's performance as another factor (Beringer et al, 2011). That is why the incident radiation on the PV panel must be maximized, which is the most important factor on PV panel's performance.

In order to obtain maximum solar radiation on PV panels must be positioned at optimum tilt angle or Solar Tracking System (STS) must be used. The purpose of solar tracking systems is to obtain maximum benefit from solar radiation by adjusting the PV panel's angle continuously throughout the day (Khatib et al, 2012). However, since STS consists of moving mechanical parts they are expensive and the probability of failure is high. In addition, STS consume energy while tracking so it may not be appropriate to use STS all the time (Benghamen, 2011). That is why it may be more efficient to adjust PV panels at optimum tilt angles at monthly, seasonal and annual basis to get maximum radiation compared to STS based system (Khatib, 2010). Optimum tilt angles of PV panels generally adjusted in a way that it is very close to the actual latitude of the PV panel to acquire maximum radiation. However, some atmospheric parameters such as the clearness index, latitude and cloudiness affect the global radiation on the surface of the PV panel. Therefore the performances of PV panels vary in different climatic conditions (Gharakhani and Pillay, 2012).

In recent years, great number of studies is conducted on determination of optimum inclination angle of PV panel. In general, radiation data of past years are used in those studies. From those radiation data, optimum inclination angle can be calculated at desired tilts using the mathematical methods (Benghamen, 2011). In addition, from those mathematical methods, monthly, seasonal and annual optimum tilt angles can be calculated. The most important parameter that affects correctness of mathematical methods is characteristics of the sky conditions. In addition, depending upon the directing of the surface of the PV panel, the preciseness of the mathematical methods can vary. Padovan and Del Col (2010) compared the results of their mathematical models with the actual values that are obtained from measuring diffuse and global radiation under the various tilt angles and surface orientation. Also it is observed that, Liu and Jordan's isotropic models and some anisotropic models can give similar results for surfaces directed to the south. Isotropic model has a good performance to obtain radiation on tilted surface under variable radiation conditions (Ayaz et al, 2017)

The mathematical models that are derived from past studies can also vary on its own merit depending upon the parameters taken into account. Regarding this subject, there are number of different methods based on atmospheric conditions, particularly in calculating diffuse radiation. When experimental outcomes and results of mathematical models are compared, it is observed that using anisotropic models sometimes may give better results for surface of not facing south. The study of Bakırcı (2012) showed that for 8 different reagions with different climatic conditions, optimum tilt angle values are different for every region during the same time period of the year. Also in a study conducted in five different cities of Malaysia, it is observed that there are 5 to 8 percentage increase in efficiency of energy outcomes of PV panels by changing tilt angle values in a monthly basis (Khatib et al, 2012).

In this study, optimum tilt angle is calculated for seven different areas of United States which are located on the same latitude (40o-41o N). Each of these seven geographical points is in various climatic zones and at different altitudes. The radiation values of those locations are monthly-basis data for one year. The global radiation reaching the horizontal surface is separated into direct and diffuse components. The optimum tilt angles at monthly, seasonal and annual basis are obtained by searching the maximum energy yield for the tilt angles of 0o to 90o and the results are listed in tables. In the end, the benefits from PV panel's optimum tilt angle on monthly, seasonal and annual basis are calculated.

2. Methodology

In this paper, optimum tilt angles of PV panels are calculated using three components of solar radiation, namely direct, diffuse and reflected beams.

The angle of declination is the angle between the line drawn from the center of the earth to the sun and equatorial plane. It is shown in Fig.1. Solar azimuth angle, is shown in Fig 2, is defined as the angle between North- South direction of earth and the projection of the line of sight to the sun on the ground.

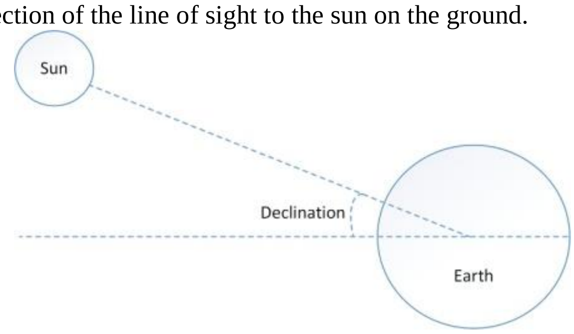

Figure 1. Declination angle

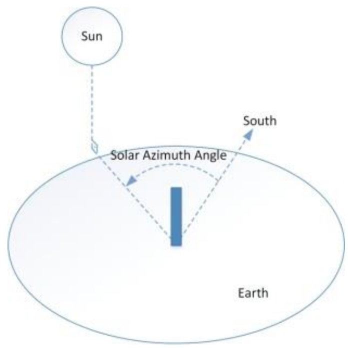

Figure 2. Solar azimuth angle

The hour angle which is expressed in angular units is an expression describing the difference between local solar time and solar noon. It is shown in Fig 3.

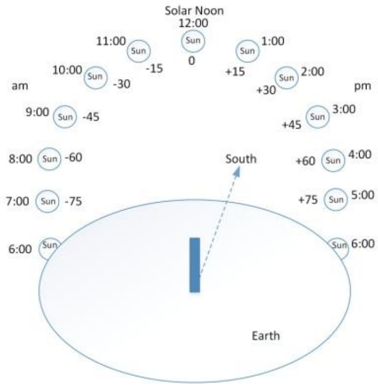

Figure 3. Hour angle

In this study, first of all hourly global solar radiation on horizontal surfaces is separated to its direct and diffuse components. Several estimation techniques are used for determining global solar radiation on horizontal surfaces (Padovan and Del Col, 2010; Chandel et al, 2005; Kamali et al, 2005; Norian et al, 2008; Chandel, 2011). Then, the solar radiation incident on inclined surface is calculated using its direct and diffuse components on horizontal surface. A number of techniques have been proposed for the estimation of solar radiation on inclined surface (Kamali et al, 2005; Norian et al, 2008; Chandel, 2011; Pandey and Katiyar, 2014).

2.1. Separation of Global Solar Radiation on Horizontal Surface to Its Direct and Diffuse Components

The measurements related with solar radiation on the earth's surface are lower than solar constant value due to the various effects of the atmosphere. The main effect is that a fraction of incoming solar radiation is reflected back into space by the atmosphere (Quaschning, 2005). This is about %30 (Chiras, 2010). Some parts of solar radiation passing through the atmosphere are absorbed by clouds, snow, water bubbles, rain, and air pollution. The remainder reaches to the earth. The total solar radiation reaching earth's surface is called global radiation. Global solar radiation on horizontal surface is composed by direct and diffuse components.

$$Ht = Hb + Hd \tag{1}$$

Measurements of the diffuse irradiance on the horizontal surface are not available though there is recorded global radiation data by many meteorological stations. However, the diffuse component of the global radiation is also required to determine of the radiation incident on inclined surface. Separation of global radiation into its components can be calculated by empirical formulas which are developed as a result of statistical studies. By using the clearness index, it is possible to separate diffuse and direct radiation from the global radiation incident to horizontal surface. The monthly average clearness index is "the ratio of monthly average daily radiation on horizontal surface to the monthly average daily extraterrestrial radiation. It can be calculated by Duffie and Beckman, (1991),

$$\bar{K}_T = \frac{\bar{H}}{\bar{H}_0} \tag{2}$$

A daily clearness index can be defined as "the ratio of a particular day's radiation to the extraterrestrial radiation for that day. It can be determined by,

$$K_T = \frac{H}{H_0} \tag{3}$$

An hourly clearness index can be calculated by the following expression,

$$k_T = \frac{I}{I_0} \tag{4}$$

where I is hourly global radiation on horizontal surface measured by a pyronometer and I_0 hourly extraterrestrial radiation. I_0 can be calculated by,

$$I_0 = \frac{24\times3600}{\pi} G_{SC}\left(1 + 0{,}033\cos\frac{360n}{365}\right) \times \left[\cos\emptyset\cos\delta(\sin\omega_2 - \sin\omega_1) + \frac{\pi(\omega_2-\omega_1)}{180}\sin\emptyset\sin\delta\right] \tag{5}$$

where GSC is the solar constant, the solar constant is taken as 1367 W/m2. n is the day of the year. $\emptyset, \delta$ and ω are latitude, declination and hour angle, respectively. In order to obtain Id/I based on kT the following expressions can be used,

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.09k_T, & k_T \le 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4, & 0.22 \le k_T \le 0.80 \\ 0.165, & k_T > 0.80 \end{cases} \tag{6}$$

Direct radiation can be calculated as Eq. (7).

$$I_b = I - I_d \tag{7}$$

where I_b and I_d are hourly direct and hourly diffuse radiations, respectively.

2.2. Calculation of Global Radiation Incident on Inclined Surface

Global radiation incident on inclined surface can be calculated by using direct and diffuse radiation on horizontal surface. Total radiation incident on inclined surface is the sum of incident direct radiation plus diffuse and reflected radiation;

$$I_T = I_B + I_D + I_R \tag{8}$$

One of the most famous models, the isotropic diffuse model, is developed by Liu and Jordan. Some terms related with diffuse radiation are ignored in this model because all diffuse radiation is assumed to be isotropic. Total radiation incident on inclined surface can be determined by follows;

$$I_T = I_b R_b + I_d R_d + I\rho R_r \tag{9}$$

Rb is the ratio of direct radiation incident on inclined surface to direct radiation incident on horizontal surface. It can be calculated by,

$$R_b = \frac{B_n \cos\theta_B}{B_n \cos\theta} \tag{10}$$

where Bn is the normal incident direct irradiance, θ_B and θ is the incidence angle of solar radiation on inclined surface and horizontal surface, respectively. The incidence angle of solar radiation on inclined surface can be calculated by;

$$\cos\theta_B = \sin\delta.\sin\emptyset.\sin\beta - \sin\delta.\cos\emptyset.\sin\beta.\cos\gamma + \cos\delta.\cos\emptyset.\cos\beta.\cos\omega + \cos\delta.\sin\emptyset.\sin\beta.\cos\gamma.\cos\omega + \cos\delta.\sin\beta.\sin\gamma.\sin\omega \tag{11}$$

where δ is the declination angle, ∅ is the latitude of the place, β is the tilt angle of panels, γ is the azimuth angle and ω is the solar hour angle. The expression of the term cosθ in Eq. (10) can be obtained by Eq. (11) when the tilt angle, β, is set equal to zero. Rd is the ratio of diffuse radiation incident on inclined surface to diffuse radiation incident on horizontal surface. For calculation of Rd, there are two different approaches; one of them is isotropic and the other is anisotropic. In this study all diffuse radiation is assumed to be isotropic so the following expression can be used for Rd;

$$R_d = \frac{(1+\cos\beta)}{2} \qquad (12)$$

The isotropic model is used for calculation of the ground reflected radiation as well as calculation of diffuse radiation so the term Rr is calculated as;

$$R_r = \frac{(1-\cos\beta)}{2} \qquad (13)$$

In this study the albedo of the ground (ρ) is set at 0.2 for all working areas. Different albedo values select for different types of surface. For unknown surfaces, the value of albedo = 0.2 is often used (Gharakhani and Pillay, 2012). So values of albedo are equal for all working areas reveal the relationship between optimum tilt angles with climatic differences more clearly at the same time.

2.3. The studied regions

In this study the optimization of tilt angles is performed for the seven different locations which approximately on the same latitude in America (40°-41° N). Seven locations used in this study are located in different climatic zones and different altitudes. So that the PV panels which are approximately on the same latitude are revealed how the optimum tilt angles of panels should be set for different climatic zones and altitude. Latitude, longitude, altitude and climatic conditions for the provinces considered in this study are given in Table 1 and their locations on the map are given in Fig 4.

Table 1. Regional latitude, longitude, latitude, and climate information

Region	Latitude	Longitude	Altitude(m)	Climate
Westhampton Gabreski (NY)	40.85	-72.633	20	Humid continental
Wooster (OH)	40.867	-81.883	346	Humid continental
Aurora (NE)	40.9	-98	548	Semi- arid
Laramie General Brees Field(WY)	41.317	-105.683	2215	Alpine
Ogden Hill Afb (UT)	41.117	-111.967	1459	Alpine
Winnemucca Municipal Arpt (NV)	40.9	-117.8	1310	Desert
Arcata Airport (CA)	40.983	-124.1	62	Mediterranean

Figure 4. Region's locations on the map

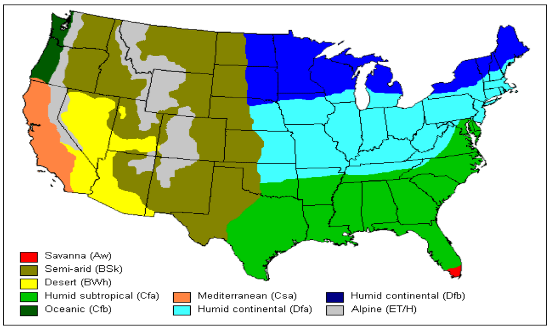

Figure 5. USA climate zones (Climate zone map USA)

These locations used in the study are located in different climatic zones. Fig. 5 shows the USA climate zones. Westhampton Gabreski and Wooster are the same climatic zones but one of them is near the sea and the other is far from the sea. Likewise, Laramie and Ogden are also the same climatic zones but their altitude is different.

3. Results and Discussions

The global radiation for Westhampton Gabreski is given in Fig. 6 for making an example of future work and direct and diffused components which are obtained depend on Kt clearness index by using MATLAB codes.

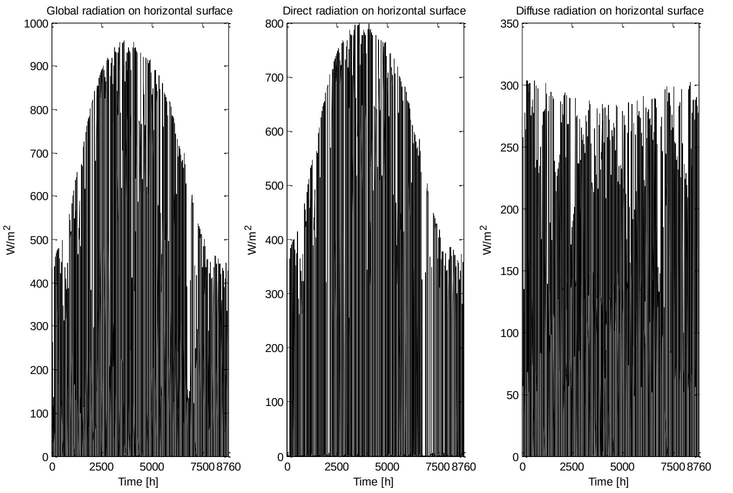

Figure 6. Global, direct and diffused radiation on horizontal surface

The direct, diffuse and reflected radiation on tilted surface is calculated using yearly direct and diffuse radiation on horizontal surface. Total annual amount of energy is obtained for every value of angle with setting β tilt angle of panel 0° to 90˚. Total annual radiation is maximum at β=31˚ for Westhampton Gabreski which located on 40.85 North latitude. Fig. 7 shows total annual amount of solar radiation for different tilt angles. Fig. 8 show direct, diffused, reflected and total solar radiation at $\beta = 31^{\circ}$, inclined surface.

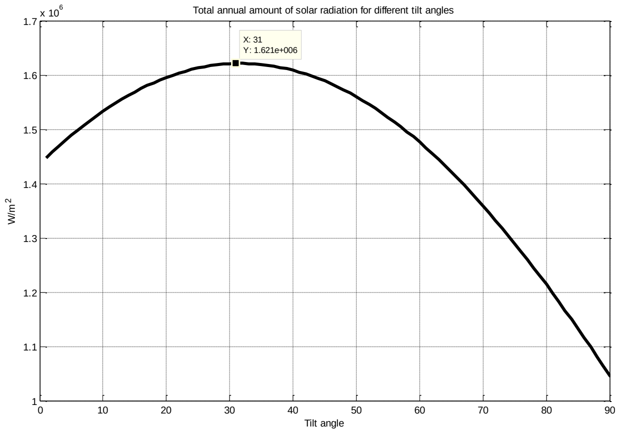

Figure 7. Total annual amount of solar radiation for different tilt angles

The calculations, which are made for Westhampton Gabreski, are repeated for other places. The annual optimum tilt angle values are given Table 2.

Table 2. Annual optimum tilt angle values

Region	Latitude	Opt. Tilt Angle
WESTHAMPTON	40.85	31
WOOSTER	40.867	28
AURORA	40.9	32
LARAMIE	41.317	33
OGDEN HILL AFB	41.117	31
WINNEMUCCA	40.9	30
ARCATA AIRPORT	40.983	29-30

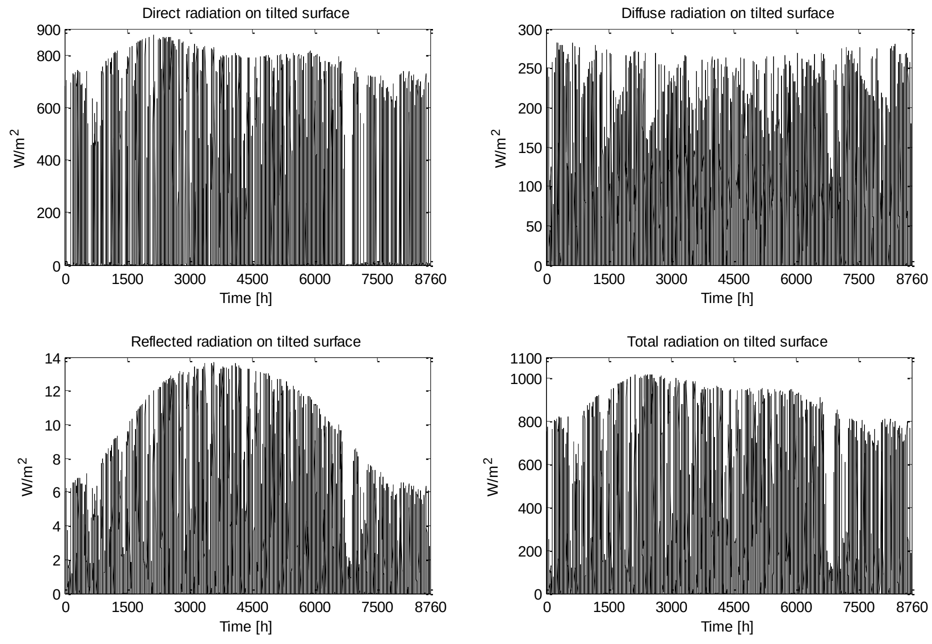

Figure 8. Direct, diffused, reflected and total solar radiation on inclined surface

It can be seen from Table 2, the optimum tilt angles can be different depending on the amount of radiation in the same climatic zone but different altitudes. Although Westhampton and Wooster are located in same climate, there are differences at the optimum tilt angles because of the sea effect. While the annual optimum tilt angle is 31˚ for Westhampton which is located near the sea, it is 28˚ for Wooster which is located in the midlands. Because Laramie which is located Alpine climate and its altitude is higher, the optimum tilt angle is 33˚ but for Ogden Hill which is in the lowlands of Alpine climate, the optimum tilt angle is 31˚. Aurora is located in semi-arid climate zone, Winnemucca is located in the desert, Arcata is located in Mediterranean climate and all of them are located same latitude, their optimum tilt angle is 32˚, 30˚ and 29˚ respectively.

The optimum tilt angle values can be different for regions which are located at the same latitude but different altitude and climate zones. The optimum angle values for Wooster can be up to 5 degrees compared with Laramie from these regions. In Table 3, the optimum angle values which should be adjusted according to the seasons is shown.

Table 3. Optimum tilt angle values per season

Region	**Optimum Tilt Angle**			
	Winter	**Spring**	**Summer**	**Autumn**
WESTHAMPTON	55	26	15	42
WOOSTER	47	26	14	41
AURORA	56	27	14	45
LARAMIE	56	27	14	46
OGDEN HILL AFB	54	27	15	46
WINNEMUCCA	51	26	13-14	45-46
ARCATA AIRPORT	51-52	26	16	43

As can be seen from Table 3 that when the weather is clearer in the spring and summer seasons, the optimum tilt angle is closer together for the 7 regions. When the weather is usually closed in autumn and winter, the optimum tilt angle can be more different.

There will be more energy gain from the panel which is positioned monthly than from panel which is positioned seasonal or annual. Therefore, the monthly optimum tilt angle calculating is important in terms of total annual energy. Table 4 shows the monthly optimum tilt angle values.

Table 4. Monthly optimum tilt angle values

Region	**Optimum Tilt Angle**											
	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
WESTHAMPTON	55-56	50-51	40	27	14-15	9	13	22	35	43	55	59
WOOSTER	51	49	39-40	27	15	10	12	22	35	44-45	52	32
AURORA	57-58	51	41	26-27	15	10	12	22	36	48-49	55-56	60
LARAMIE	60	53	41-42	27	14	7	12	22-23	36	50	57	60
OGDEN HILL AFB	54	52	42	27	14-15	10	12	23	37	49	56	58
WINNEMUCCA	37	50-51	42	26	13	7	11	22	36	49-50	56-57	58
ARCATA AIRPORT	51-52	49	39	26	14	10-11	13	23	35-36	46	53	55

It is deduced from Table 4 that the optimum tilt angle is less different for the months which is clear as well as seasonal positioning. The optimum tilt angle is very low for Wooster in December and it is low for Winnemucca in January. In the study, 1-year data are used. Thus, temperatures of the weather could be realized unseasonable in certain months for taken into consideration of year.

4. Conclusion

The optimum tilt angle for PV panels positioned at a fixed angle has a critical importance to receive the maximum power output in a system design. This study has shown that the optimum tilt angle of fixed PV panels can be different for locations which are at the approximately same latitude but in different climate zones considering only radiation data. Therefore, the meteorological data is extremely important to take into consideration in PV system design. Total annual amount of energy which is calculated by annual / seasonal / monthly optimum angle obtained in MATLAB increase between 1.75% and 3.34% when it is positioned as seasonal with respect to annual. Similarly, if the monthly optimum angle is used instead of annual optimum angle the gain in energy is up to 4.19% for seven regions. In the winter months, the difference between optimum tilt angles of PV panels which are located approximately on the same latitude but in different climatic conditions is more noticeable due to cloudiness. This study is carried out for provinces which are located in different climate zones considering only the radiation data. If other meteorological data (temperature, wind, humidity, etc.) are taken into account beside solar radiation, it is possible to get different results.

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