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Performance Evaluation of a Pseudo Two-axis Sun Tracking System

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Abstract

Tracking the sun is an important method for increasing the electricity generation of photovoltaic panels. Sun tracking systems are designed to track the sun with one axis or two axes, based upon solar azimuth angle and altitude angle. In this research, a pseudo two-axis sun tracker is presented and applied for installing the photovoltaic panel on. In this tracking system, one rotating motor is used instead of two, and more solar radiation is absorbed compared with common one-axis tracking systems. The results show that pseudo two-axis sun tracking system gains 2.82% more radiation than the conventional one-axis sun tracker. Through adjusting the angle two times a year, 4.01% more radiation is gained and adjusting the angle four times a year results in gaining 4.12% more radiation, while using a two-axis sun tracker results in 4.39% more radiation on the panel compared with one-axis sun tracker. The pseudo two-axis sun tracker's performance with adjusting angle four times a year has little difference with two-axis sun tracker and due to using one motor instead of two, using a pseudo two-axis sun tracker is more economical. The percentage of increased radiation of pseudo two-axis sun tracker compared with fixed panel differs for various cities, which could be as high as 31% for some major Iranian cities.

Keywords: Solar angles; Photovoltaic panel; Sun tracking system; Pseudo two-axis tracker; Optimum angle

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1. Introduction

Solar energy is renewable, clean and abundant. Photovoltaic (PV) systems are used to convert solar energy into electrical energy. The amount of generated electrical energy can be increased by tracking the sun. Sun tracking systems are designed to track the sun with one axis (according to the azimuth angle) or two axes (according to the solar azimuth and altitude angles). In recent years, various studies have been conducted on sun tracking systems, which have used a number of different methods.

Abdallah and Nijmeh [1] designed and constructed an electromechanical two-axis sun tracking system. Conducting an experimental study, they investigated the effect of using two-axis tracking on collecting solar energy. The results of their study revealed that the collected energy on the

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tracking surface was approximately 41% more than the collected energy on the fixed one inclined at 32°. Taking advantage of a two-axis sun tracking system to improve the efficiency of a parabolic trough collector, Bakos [2] performed a study in Greece. The experiment was conducted in both clear and cloudy weather conditions. The tracking was controlled through a photo-sensor and a software working in all weather conditions regardless of the presence of clouds; the photo-sensor and the software could be used both with each other and separately. The study results showed that the tracking surface received more solar energy (up to 46.46%) than the fixed surface. It was also found that in the cloudy and rainy weather conditions in the middle of the day, when the collector's movement was merely controlled through the software (without the light sensor), there was a significant decrease in the generated power. In another study, Sungur [3] calculated the solar azimuth and altitude angles of the sun for a period of one year in Turkey. The results of his study revealed that the two-axis sun tracking system led to 42.5% more energy gain in comparison with the fixed system. Sefa et al. [4] investigated the effect of one-axis sun tracking system on the electrical generation of 2500 W solar panels located in Turkey. The electromechanical mechanism was designed for the movement of solar panels in East-West directions, and the movement procedures were controlled using photo resistors. In the measurement strategy for solar systems, based on PC, the fixed and the tracking solar systems collected data at the same day with the same mechanism. Daily energy production of the system was about 17.248 kWh with tracking and about 11.862 kWh without tracking. Thus, the tracking system produced 45% more electrical energy than the fixed system in the measurement day, and it had better performance. Chang [5] calculated the radiation on a single-axis tracked panel using mathematical expressions. The yearly optimal tilt angle of a fixed panel was found to be approximately 0.8 times latitude. According to the results, radiation on a single-axis tracked panel was more than the radiation on a fixed panel. This gain was between 20.0% and 33.9% for four specified days of year, between 20.9% and 33.2% for the four seasons and 27.6% over the entire year. Li et al. [6] investigated the optical performance of vertical single-axis tracked solar panels in China. The results of the mathematical procedure revealed that annual collectible radiation, following the use of tracker, was increased by 28% in the areas with abundant solar resources and increased by 16% in the areas with poor solar resources, compared with fixed solar panels. In another study, Maatallah et al. [7] examined the performance of fixed photovoltaic panels as well as one-axis and two-axis tracking panels in Tunisia. The findings of their study in case of the fixed and two-axis tracking panels revealed that the use of two-axis tracking panel in comparison with the traditional fixed panel led to obtaining 30% and 44% more energy in the winter and summer solstice days.

Chin et al. [8] designed, modeled, and tested an active single-axis solar tracker. The computer model of the stand-alone solar tracker system was modeled using MATLAB/Simulink, which was in accordance with the experimental model. The results of the study revealed that the efficiency of the smart tracking panel was approximately 20% more than that of the fixed panel. Colli and Zaaiman [9] tested three solar panels using different forms of crystalline silicon in Italy. They proposed a methodology based on the effective maximum power of the PV modules which was applied to the fixed and one-axis sun tracking systems. The study showed that PV modules installed on the single-axis tracker had better performance than the fixed PV module. The total monthly irradiance gained by one-axis tracker was 19% and 23% more than the irradiance on fixed module for March and April, respectively. Huang et al. [10] dealt with a low-cost sun tracking system. They used a one-axis three-position system to track the sun. Tracking the sun was conducted three times a day. The study findings indicated 25.4% increase in the generated power in a period of nine months in Taiwan, which is an area of low solar energy resource. Eke et al. [11] have analyzed performance results of double-axis sun tracking photovoltaic systems after one year of operation. Two identical 7.9 kWp PV systems with similar modules and inverters were installed and tested at Mugla University. Results showed that 30.79% more PV electricity was obtained in the double-axis sun tracking system when compared with the fixed system. In another piece of research, Jafarkazemi et al. [12] found the optimum tilt angle for south facing flat-plate solar collectors in Iran. A mathematical model was used for estimating solar radiation at different tilt angles. Based upon the study results, it was recommended to adjust tilt angles at least twice a year. Optimum tilt angles for cloudy sky cities with a low clearness index were lower than those for cities at the same latitude angle having a higher clearness index. It was found that in addition to latitude angle, the climate conditions were also important for determining the optimum tilt angle. Ingenhoven et al. [13] compared the obtained energy in one-axis and two-axis tracker panels and fixed panel. The study was conducted in the Italian Alps. The findings showed that one-axis and two-axis sun tracking systems generated 22% and 25-26% more electricity in comparison with the fixed panels, respectively.

Despotovic and Nedic [14] determined the optimum tilt angles of solar collectors in Serbia at yearly, seasonal and monthly levels. They calculated annually collected energy per square meter of tilted surface for ten different scenarios (see Figure 1). By defining seasons as solar seasons, optimum tilt angles for spring and summer were very similar and also optimum tilt angles for autumn and winter were very similar. They concluded that for such seasonal scenario, it was not necessary to adjust tilt angle four times a year and adjustment twice a year, at the beginning of spring and autumn, would suffice. The case study of simulated buildings showed that the yearly energy gain obtained by placing the panels at yearly, seasonal and monthly optimum tilt angles, compared with energy gain from fixed panels was increased by factor of 5.98%, 13.55% and 15.42%, respectively.

Lazaroiu et al. [15] compared the PV power production of a panel installed on single-axis sun tracker with fixed panel, considering energy consumption. The output power was measured in different weather conditions. Results indicated that the single-axis sun tracker increased 12-20% of the produced energy, and the growth was maximized during clear sky days.

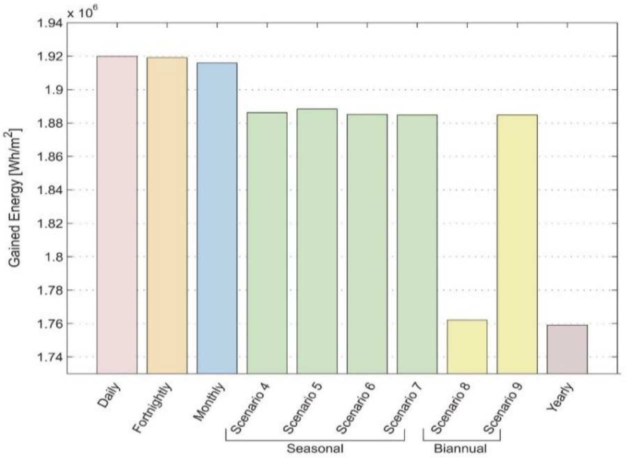

Figure 1. Comparison of total gained energy at different scenarios [14]

Bruno et al. [16] considered small-size single-axis PV trackers. A parametric study in function of the axis inclination angle was conducted in order to maximize the yearly beam solar radiation. When the modules were rotated according to the solar azimuth angle, collected beam radiation increased 23.6% compared with a fixed system. By optimizing rotation angle, collected radiation was found to be 27.5% greater than the fixed module surface tilted by 30°. Fathabadi [17] examined an offline sensorless dual-axis sun tracker, so the cloudy weather didn't affect the operation of the system. According to experimental results, 24.59% more solar energy was gained during a year by using the sun tracker. Sharaf Eldin [18] et al. investigated the effect of sun tracking and temperature on performance of a PV panel. The results showed that tracking the sun in cold regions was more economical than tracking in hot regions.

Seme et al. [19] analyzed single axis and dual axis tracking systems. A new control model of tracking was defined to maximize the energy production of PV tracking system by the second derivative of the produced energy. They concluded that a higher yield of energy production with the new approach can be achieved compared to the step by step tracking system, and this higher yield could be up to 2% on an annual basis. Lee et al. [20] developed a scheme for one-axis sun trackers. It was based on one-axis three-position sun tracker, and it automatically identified the optimal stopping angle for the PV module. The photovoltaic module was rotated in 100 degrees to determine the optimal angle where the maximum power is produced, and it was rotated once per hour. The amount of generated electric energy was increased by avoiding shading from clouds, buildings and other PV panels. Saymbetov et al. [21] presented an algorithm for a dual-axis schedule tracker in cloudy weather. The developed method of tracking for scattering of the sun's rays by clouds was more efficient than the conventional dual-axis trackers. Jamroen et al. [22] designed a dual-axis solar tracking system for PV panels using UV sensors. Results show that the tracking system increases the energy generation by 20% and 11% compared with the fixed system and LDR-based tracking system, respectively.

Antonanzas et al. [23] investigated the environmental differences between fixed and tracking PV systems. Results indicated that the avoided greenhouse gas emission at tracking systems is more than the fixed systems, because manufacturing PV panels generates more pollution than producing a tracking structure. Kang et al. [24] concluded that the electricity generation by direct sun tracking system was 12.9% more than indirect tracking method. They considered effect of climate factors [25] and concluded that when the amount of clouds is below 95%, direct tracking results in generating more electricity than indirect tracking. Hoffmann et al. [26] compared a two-axis solar tracking system with a fixed system in Brazil. Results indicated 17.2%-31.1% more irradiation on the tracking system than the fixed system. In general, sun tracking systems could be divided into astronomically-controlled and sensor-controlled systems. In astronomically-controlled systems, the sun is tracked in a predetermined path. In sensor-controlled systems, the motion of motor is controlled through evaluating the signals received from the photo-sensors placed on the PV panel. In such systems, unstable states may exist under overcast and partly cloudy weather conditions, when the photo-sensors do not see the sun. Hence, a predetermined path is used in the present research. It is noteworthy that optimum path can be determined for every city in the world by knowing its latitude.

In order to receive the most irradiation from the sun, a two-axis sun tracker is needed to move the panel as solar azimuth angle and solar altitude angle changes to hold it perpendicular to the sun. However, in flat plate collectors, a small change in position doesn't have much effect on the performance. Therefore, using one-axis sun trackers instead of two-axis trackers for flat plate collectors could omit the expenses of second motor, second controlling system, and maintenance cost. Additionally, the use of one-axis sun tracker largely increases received radiation compared with the fixed panel; however, received radiation by two-axis tracker has little increase compared with one-axis tracker. In this research a one-axis tracker, which receives more radiation than the common one-axis tracker, is used. It is named pseudo two-axis sun tracker. The pseudo two-axis sun tracker is used for installing a photovoltaic panel on, and it tracks the sun from morning to night. The calculated solar energy on the pseudo two-axis tracker is compared with that on one-axis and two-axis trackers. The results of changing angle a few times in a year are investigated. The optimum adjustment angles for pseudo two-axis tracker, as well as the increased energy compared with fixed panel are calculated for major Iranian cities.

2. Methodology

In the pseudo two-axis sun tracker, axis of rotation makes angle α_1 with the normal vector of ground, and the angle between the photovoltaic panel and axis of rotation is α_2. A schema for the mechanism is shown in Figure 2.

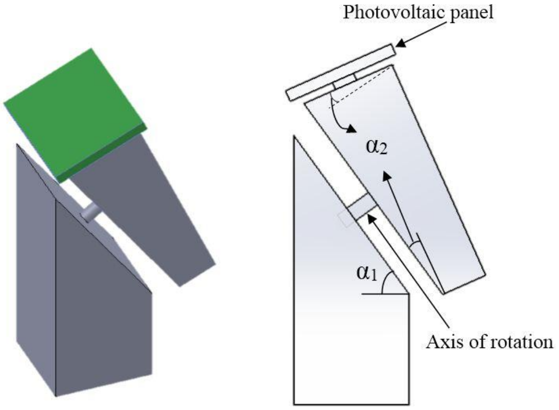

Figure 2. Pseudo two-axis sun tracker

The angle α_2 can be adjusted a few times a year, so that changes of solar altitude angle in a year can be applied to the pseudo two-axis sun tracker.

Slope of the photovoltaic panel with pseudo two-axis sun tracker changes with time and the slope can be approximated as:

$$\beta = 90 - \alpha_2 + \left(\frac{t-18}{6} \right) \alpha_1 \tag{1}$$

At 12 o'clock, the panel has slope of 90-(α_1+α_2) degrees. Slope of the panel at 6 o'clock and 18 o'clock is approximately 90-α_2, and the following calculations for 18 o'clock show that the approximation of slope has little difference with the exact value.

Figure 3 depicts a schema of the mechanism at 18 o'clock, and exact calculations for slope of the panel are made as follows.

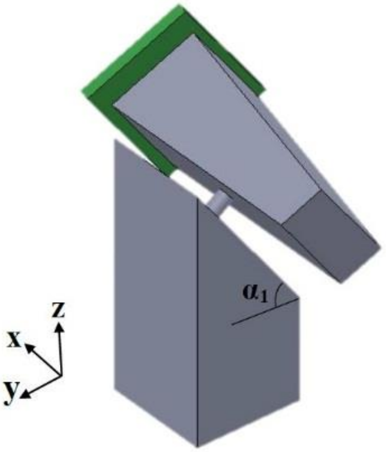

Figure 3. Pseudo two-axis sun tracker at 18 o'clock

If α_1 were zero, normal vector of the panel in x-z plane would be l=(cos α_2, 0, sin α_2). The normal vector of the panel with arbitrary values of α_1 and α_2 can be calculated by rotating l about x-axis through angle α_1.

$$l' = R_x(\alpha_1) l = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha_1 & -\sin\alpha_1 \\ 0 & \sin\alpha_1 & \cos\alpha_1 \end{bmatrix} \begin{bmatrix} \cos\alpha_2 \\ 0 \\ \sin\alpha_2 \end{bmatrix} = \begin{bmatrix} \cos\alpha_2 \\ -\sin\alpha_1 \sin\alpha_2 \\ \cos\alpha_1 \sin\alpha_2 \end{bmatrix} \tag{2}$$

Slope of the panel is the angle between normal vector of the plane, l', and vertical vector p=(0, 0 1).

$$\cos\beta = \frac{l'.p}{|l'||p|} = \frac{(\cos\alpha_2, -\sin\alpha_1\sin\alpha_2, \cos\alpha_1\sin\alpha_2).(0,0,1)}{\left(\sqrt{(\cos\alpha)^2 + (\sin\alpha)^2}\right)(1)} = \cos\alpha_1 \sin\alpha_2 \tag{3}$$

According to the calculations for radiation on a plane (mentioned later), the optimum values of α_1 and α_2 for receiving the most yearly radiation in Isfahan (32°50'N, 51°50'E) are respectively 54° and 12°. Thus, the approximate and exact values of the slope at 18 o'clock are:

Approximate value:

$$\cos\beta = \cos(90 - \alpha_2) = \sin\alpha_2 \Rightarrow \beta = 78.00° \tag{4}$$

Exact value:

$$\cos\beta = \cos\alpha_1 \sin\alpha_2 \Rightarrow \beta = 82.98° \tag{5}$$

The comparison of two last equations shows that at 18 o'clock, the difference between approximate and exact values of slope is less than 5°. Therefore, the variation of slope with time could be expressed as β=90-α_2+((t-18)/6)α_1, which yields exact value at 12 o'clock and has good accuracy at 18 o'clock. Considering that solar radiation intensity is much weaker at early morning and late afternoon hours, the difference between the exact and approximate slopes has no significant effect on the power generation.

The required calculations for isotropic sky has been done by Duffie and Beckman [27]. Accordingly, extraterrestrial radiation on a horizontal surface, H_0, for nth day of year is:

$$H_0 = \frac{24 \times 3600 G_{sc}}{\pi} \left(1 + 0.033 \cos\frac{360n}{365} \right) \times \left(\cos\phi \cos\delta \sin\omega_s + \frac{\pi\omega_s}{180} \sin\phi \sin\delta \right) \tag{6}$$

where ω is hour angle and ω_s is sunset hour angle, G_{sc} is the solar constant and has a value of 1367 W/m^2.

Declination (δ) is the angular position of the sun at solar noon with respect to the plane of the equator, and it can be found from equation (7).

$$\delta = 23.45\sin\left(360\frac{284+n}{365}\right) \tag{7}$$

Zenith angle (θ_z) is the angle between the vertical and the sun.

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta \tag{8}$$

The sunset hour angle (ω_s) is calculated by equation (9), when θ_z=90° in equation (8).

$$\cos\omega_s = -\tan\phi\tan\delta \tag{9}$$

Solar azimuth angle (γ_s) is the angular displacement from south of the projection of beam radiation on the horizontal plane. It can be found from equation (10).

$$\gamma_s = sign(\omega)\left|cos^{-1}\left(\frac{\cos\theta_z\sin\phi-\sin\delta}{\sin\theta_z\cos\phi}\right)\right| \tag{10}$$

In pseudo two-axis sun tracking, the surface azimuth angle is equal to solar azimuth angle.

Clearness index (K_T) is the ratio of daily radiation on a horizontal surface to the extraterrestrial radiation, and daily clearness index (K_T) is calculated by data of monthly clearness index [28].

$$K_T = \frac{H}{H_0} \tag{11}$$

The data for clearness index is available for each month. Clearness index for all days of a year can be gained by curve interpolation through the average days of each month, under the constraint of equal value of clearness index for n=1 and n=366.

The ratio of hourly total to daily total radiation, r_t, is calculated by the following equation.

$$r_t = \frac{I}{H} = \frac{\pi}{24}(a+b\cos\omega)\frac{\cos\omega-\cos\omega_s}{\sin\omega_s-\frac{\pi\,\omega_s}{180}\cos\omega_s} \tag{12}$$

where a and b are calculated by equations (12.a) and (12.b):

$$a = 0.409 + 0.5016\sin(\omega_s-60) \tag{12.a}$$

$$b = 0.6609 - 0.4767\sin(\omega_s-60) \tag{12.b}$$

The ratio of hourly diffuse to daily diffuse radiation, r_d, is calculated by the following equation.

$$r_d = \frac{I_d}{H_d} = \frac{\pi}{24}\frac{\cos\omega-\cos\omega_s}{\sin\omega_s-\frac{\pi\,\omega_s}{180}\cos\omega_s} \tag{13}$$

Diffuse component of daily radiation, H_d/H, is a function of the day's clearness index and could be calculated as follows:

$$\frac{H_d}{H} = 1.188 - 2.272K_T + 9.473K_T^2 - 21.865K_T^3 + 14.648K_T^4 \tag{14}$$

The ratio of beam radiation on the tilted surface to that on a horizontal surface is the geometric factor.

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{15}$$

Radiation on a photovoltaic panel tracking the sun with pseudo two-axis sun tracker is calculated by the equation of radiation on sloped surfaces. The radiation on the tilted surface include beam, isotropic diffuse and solar radiation diffusely reflected from the ground:

$$I_T = I_bR_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I\rho_g\left(\frac{1-\cos\beta}{2}\right) \tag{16}$$

The daily solar radiation is obtained by summing the hourly radiation during that day and the yearly solar radiation in each angle of α_1 and α_2 is calculated by summing the daily radiation. The yearly solar radiation on the inclined surface with pseudo two-axis sun tracker is compared in different angles of α_1 and α_2 varied from 1° to 90° in the steps of 1° in order to find the yearly optimum angle.

The seasonal solar radiation in each angle of α_1 and α_2 is calculated by summing the daily solar radiation in that season, and this procedure is used for determining the seasonal, declination-based, biannual, and yearly radiation in each angle.

3. Results & Discussion

3.1. Radiation on a panel with pseudo two-axis tracker for all days of the year

The radiation on flat photovoltaic panel with one-axis, pseudo two-axis, and two-axis sun trackers is calculated for one year. The result for Isfahan is shown in Figure 4 for all days of the year.

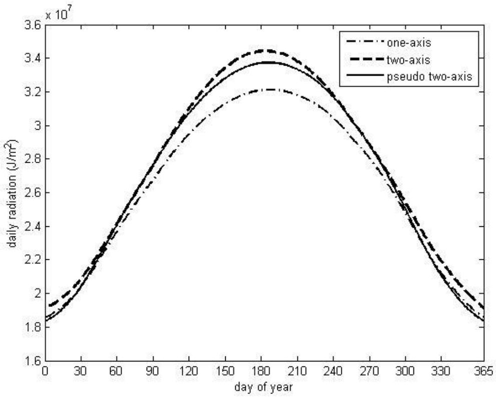

Figure 4. Radiation on panel with one-axis, pseudo two-axis, and two-axis sun trackers at Isfahan

Figure 4 shows that the radiation on the panel with two-axis sun tracker is more than the radiation on the panels with pseudo two-axis and one-axis trackers for all days of the year. The underlying reason is that with a two-axis sun tracker, surface azimuth angle and slope of panel are adjusted such that the beam radiation is normal to the panel for any hour and all days of the year. The radiation on the panel with pseudo two-axis sun tracker is more than the radiation on the panel with one-axis sun tracker. In 60th to 300th day of the year, the radiation with pseudo two-axis sun tracker has a value close to radiation on the panel with two-axis sun tracker while less radiation is gained by the one-axis sun tracker. Just in the first and last 30 days of the year, the radiation with pseudo two-axis sun tracker is a little less than one-axis sun tracker. Better radiation on pseudo two-axis sun tracker at most days of the year results in more yearly radiation on this sun tracker compared with the one-axis tracker. In the 60th to 90th day of the year as well as the 240th to 270th day, pseudo two-axis sun tracker has almost the same performance as the two-axis tracker. The yearly radiation gained by the one-axis, pseudo two-axis and two-axis sun trackers are respectively 9658 MJ/m^2, 9930 MJ/m^2 and 10082 MJ/m^2.

The pseudo two-axis sun tracker has better performance compared with the one-axis tracker, and it does not have much difference with the two-axis tracker. It will be shown that if the angle is adjusted a few times a year for the pseudo two-axis sun tracker, we will have almost the same performance as the two-axis tracker. Using one motor instead of two, one control system, less initial cost and less maintenance expenses are among the benefits of applying pseudo two-axis rather than two-axis sun tracker.

If the angles of α_1 and α_2 will be constant in a year, the optimum angles for gaining the most radiation on the photovoltaic panel are α_1=54° and α_2=12° for Isfahan and the amount of yearly radiation is 9930 MJ/m^2.

3.2. Results of changing angle a few times a year

a Solar altitude angle changes during a year. If the angle α_2 is adjusted a few times a year, there is more radiation on the photovoltaic panel and more electrical power is generated. The number of changing angle and the day of changing affect the photovoltaic panel's performance.

3.2.1. Changing angle two times a year considering cool and warm time periods

One criterion for adjusting the angle of pseudo two-axis sun tracker is the application of the panel installed on the tracker. If a photovoltaic panel is installed on tracker for generating electrical power, hot seasons of the year are more important because more radiation exists in those seasons. If a solar collector is installed on the pseudo two-axis tracker, cool seasons of the year are more important due to more demand for warm water in cool seasons, especially for domestic applications. Therefore, one criterion for adjusting the angle α_2 is radiation in warm and cold seasons. In this case, biannual adjustment is needed, that is changing angle two times a year, in the first day of spring and the first day of autumn. The angle α_1 is set to optimum angle in the whole year, and the angle α_2 is changed twice a year.

In the case of generating power application, calculations are made for six warm months of the year. The optimum angle for pseudo two-axis sun tracker is α_2=20°, and the gained radiation at this time is 5930 MJ/m^2. In the second case, that is, producing warm water for cool seasons, calculations are made for six cold months of the year. The optimum angle is α_2=0°, and the gained radiation at this time is 4115 MJ/m^2. So in case of biannual adjustment, total radiation in a year is 10045 MJ/m^2, which is 1.16% more than the amount when constant angle α_2 is used for a year.

If both angles of α_1 and α_2 are adjusted on the first day of spring, the most radiation is gained when α_1=66° and α_2=14° and the panel gains radiation with the amount of 5940 MJ/m^2. If both angles of α_1 and α_2 are adjusted on the first day of autumn, the optimum angles are α_1=47° and α_2=5° and the radiation on collector will be MJ/m^2. So in case of biannual adjustment of both angles α_1 and α_2, total radiation in a year is 10057 MJ/m^2, which is 1.28% more than that of the time when constant angles α_1 and α_2 are used for a year.

3.2.2. Changing angle four times a year

A good criterion for adjusting angle is considering declination. Declination varies between -23.45° and 23.45°. Two ways of changing angle according to declination are proposed.

First case:

In this case, angle of α_2 is changed when δ is maximum or minimum. So the angle should be changed on the first day of seasons. Figure 5 shows declination and days of adjusting the angle α_2.

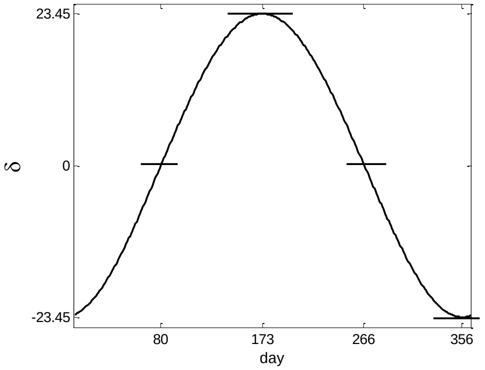

Figure 5. Dividing declination on the first day of each season

When the angle α_1 is equal to the value for yearly optimum radiation (α_1=54°), the optimum angle of α_2 for setting at the beginning of each season and corresponding seasonal radiation is presented in Table 1.

Table 1. The optimum angle of α_2 for adjustment on the first day of each season and radiation for that season

Season	Optimum angle of α_2 (°)	Radiation (MJ/m^2)
spring	20	2890
summer	20	3040
autumn	0	2174
winter	0	1941
total		10045

An important result of Table 1 is that the optimum angle for summer is equal to the angle for spring, and the optimum angle for winter is equal to the angle for autumn. This is the biannual adjustment case which was discussed before. The angle of α_2 is adjusted at the beginning of spring and autumn. Similar result was observed by Despotovic and Nedic [14] for fixed collectors. They determined the optimum tilt angles of solar collectors for Serbia at yearly, seasonal and monthly levels. Ten different scenarios were considered. One scenario was adjusting the angle at the beginning of each season. The researchers found that if seasons were defined as solar seasons, the optimum tilt angles for spring and summer were very similar, as well as autumn and winter. This finding led to the conclusion that for such a seasonal scenario it was not necessary to adjust tilt angle four times a year and adjustment twice a year, at the beginning of spring and autumn, would suffice.

The yearly radiation in this case is 10045 MJ/m^2 which is 1.16% more than that of when constant angle α_2 is used for a year.

Second case:

In this case the angle α_2 is adjusted according to the rate of declination change. Total change in δ is divided into four equal parts as shown by Figure 6. In the case, the angle α_2 is adjusted on the 50th, 111th, 235th and 298th day of year corresponding to 19 February, 21 April, 23 August and 25 October, respectively.

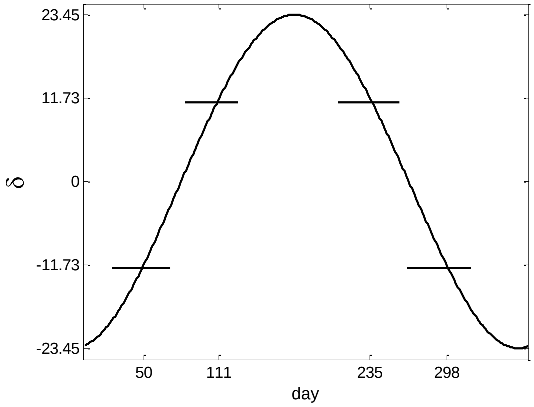

Figure 6. Dividing declination

When the angle of α_1 is equal to the value for yearly optimum radiation, the optimum angle of α_2 for being set based upon Figure 6, as well as radiation in corresponding periods is presented in Table 2.

Table 2. The optimum angle of α_2 for adjustment according to the rate of declination change and radiation in corresponding periods

Day	Number of day	optimum angle of α_2 (°)	Radiation (MJ/m^2)
19 Feb -20 Apr	50-110	12	1614
21 Apr -22 Aug	111-234	22	4109
23 Aug -24 Oct	235-297	10	1832
25 Oct -18 Feb	298-365 & 1-49	0	2501

The yearly radiation in this case is 10056 MJ/m^2 which is 1.27% more than that of when constant angle α_2 is used for a year.

Since in the first case 1.16% more radiation is gained compared with that of the constant angle of α_2 and in the second case 1.27% more radiation is gained, the second case is considered to be better. Therefore, the angle of α_2 should be changed on 19 February, 21 April, 23 August and 25 October, and the value of the angle should be set according to Table 2.

3.3. Comparison of different sun tracking systems

Different ways of sun tracking lead to different amounts of radiation on photovoltaic panel installed on the tracker and consequently different amounts of generated power. Table 3 shows the gained radiation by different sun trackers, and the radiation enhancement compared with one-axis sun tracker.

Table 3. Radiation gained by different ways of tracking the sun

Sun tracker	Yearly radiation (MJ/m^2)	Radiation enhancement compared with one-axis sun tracker (%)
one-axis (with fixed slope)	9658	
Tilted one-axis	9898	2.48
Two-axis	10082	4.39
Pseudo two-axis with adjusted angle for year	9930	2.82
Pseudo two-axis with biannual adjustment	10045	4.01
Pseudo two-axis with adjustment by declination	10056	4.12

As shown in Table 3, the photovoltaic panel with pseudo two-axis sun tracker gains 2.82% more radiation compared with one-axis sun tracker and 4.12% more radiation is obtained by adjusting the angle four times a year.

3.4. The optimum angles for major Iranian cities

Different cities have different latitude and clearness index, and it affects the optimum angle for pseudo two-axis sun tracker. Nematollahi et al. [28] have calculated clearness index for major cities in Iran. Regarding Isfahan, the optimum angles for pseudo two-axis sun tracker are $\alpha_1=54°$ and $\alpha_2=12°$, as the results were presented. For major Iranian cities, the yearly radiation gained by fixed panel tilted toward the south is presented in Table 4. Additionally, Table 5 reveals the yearly optimum angles and radiation gained by pseudo two-axis sun tracker, as well as the increased radiation compared with the fixed panel.

Table 4. Calculated yearly radiation for fixed panel for major Iranian cities

City	ϕ (°)	$\beta_{opt.}$ (°)	Yearly radiation (MJ/m^2)
Bandar Abbas	27.2	19	6643
Birjand	32.9	26	7878
Bojnurd	37.5	27	6641
Hamadan	34.8	25	7328
Isfahan	32.6	26	7713
Jask	25.6	19	6983
Kerman	30.3	24	7908
Mashhad	36.3	24	6303
Orumiyeh	37.6	30	7639
Shiraz	29.6	23	7695
Tabas	33.6	25	7335
Tehran	35.7	21	6200
Yazd	31.9	23	7922
Zahedan	29.5	20	6368
Zanjan	36.7	29	7147

Table 5. Calculated optimum angles and yearly radiation with pseudo two-axis sun tracker for major Iranian cities

City	ϕ (°)	$\alpha_{1,opt}$ (°)	$\alpha_{2,opt}$ (°)	Yearly radiation (MJ/m^2)	Increase compared with fixed panel (%)
Bandar Abbas	27.2	55	18	7730	16.4
Birjand	32.9	55	11	10265	30.3
Bojnurd	37.5	48	16	8143	22.6
Hamadan	34.8	53	13	9359	27.7
Isfahan	32.6	54	12	9930	28.7
Jask	25.6	59	15	8300	18.9
Kerman	30.3	57	11	10216	29.2
Mashhad	36.3	48	19	7507	19.1
Orumiyeh	37.6	47	13	9961	30.4
Shiraz	29.6	58	11	9789	27.2
Tabas	33.6	53	13	9278	26.5
Tehran	35.7	51	19	7355	18.6
Yazd	31.9	57	11	10391	31.2
Zahedan	29.5	52	20	7314	14.8
Zanjan	36.7	49	14	9002	26.0

The presence of clouds in sky affects gained radiation in days of a year. Therefore, the optimum angle for a fixed panel depends on the latitude and clearness index of the city which is considered.

As it is shown in Table 5, tracking the sun with pseudo two-axis sun tracker increases the amount of gained radiation compared with fixed panel. The percentage of this increase differs for major Iranian cities, which could be as high as 31% for some of these cities.

3.5. Comparison of daily radiation gained through various sun trackers

Radiation on panel in hours of a day differs according to the type of sun tracker. Figure 7 shows the radiation at the first day of spring gained through one-axis, pseudo two-axis with annually optimized angle and two-axis sun trackers. Radiation for other days of the year could be calculated similarly.

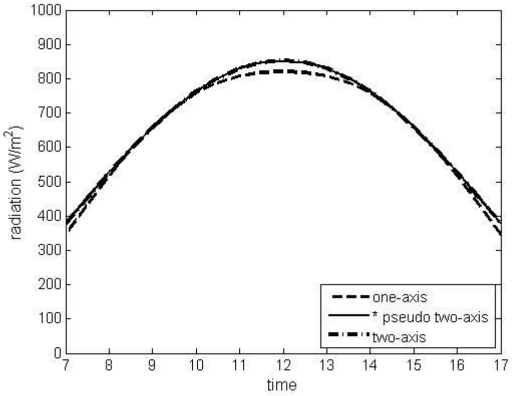

Figure 7. Daily radiation at the first day of spring with one-axis, pseudo two-axis and two-axis sun trackers.

As shown in Figure 7, the radiation on panel with two-axis sun tracker is more than the radiation on panels with pseudo two-axis and one-axis trackers. The reason is that with a two-axis sun tracker, surface azimuth angle and slope of panel is adjusted such that the beam radiation is normal to the panel for any hour. The radiation on panel with pseudo two-axis sun tracker is more than the radiation on panel with one-axis sun tracker, and there does not exist much difference between pseudo two-axis tracker and two-axis tracker at the first day of spring.

4. Conclusions

a One important method for increasing the capacity of electricity generation by photovoltaic panels is tracking the sun. Yearly radiation on a photovoltaic panel with pseudo two-axis sun tracker is more than the radiation on a panel with one-axis sun tracker. For adjusting the angle of α_2 on the beginning of each season, the optimum angle for summer is equal to the angle for spring, and the optimum angle for winter is equal to the angle for autumn. It leads to the conclusion that adjusting the angle of α_2 twice a year, at the beginning of spring and at the beginning of autumn, has the same result as adjusting the angle four times a year at the beginning of each season.

Pseudo two-axis sun tracker gains 2.82% more radiation in a year compared with one-axis sun tracker. Adjusting the angle two times a year results in 4.01% more radiation, and adjusting the angle four times a year according to declination angle results in 4.12% more radiation compared with one-axis sun tracker. Pseudo two-axis sun tracker's performance with adjusting angle four times a year has little difference with two-axis sun tracker and due to using one motor instead of two, using a pseudo two-axis sun tracker is more economical. The percentage of increased radiation of pseudo two-axis sun tracker compared with fixed panel differs for various cities, which could be as high as 31% for some of major Iranian cities.

Nomenclature

G_{sc}	Solar constant, W/m^2
H	Daily radiation on a horizontal surface, J/m^2
H_0	Extraterrestrial daily radiation on a Horizontal surface, J/m^2
H_d	Daily diffuse radiation, J/m^2
I	Hourly radiation, J/m^2
K_T	Clearness index, dimensionless
n	The number of the day
R_b	Geometric factor
r_t	Ratio of hourly total to daily total radiation
r_d	Ratio of hourly diffuse to daily diffuse radiation
Greek symbols	
α_1	The angle between axis of rotation and normal vector of ground, degree
α_2	The angle between photovoltaic panel and axis of rotation, degree
β	Slope of the panel, degree
θ	Angle of incidence, degree
θ_z	Zenith angle, degree
γ_s	Solar azimuth angle, degree
ρ	Reflectivity of the ground, dimensionless
δ	Declination angle, degree
ϕ	Latitude, degree
ω	Hour angle, degree

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