Design and Performance of Two Axes Solar Tracker

S. Soulayman[1,*], W. Sabbagh[1], M. Hamoud[1] and A. Sanduk[2]

[1]Dept. of Applied Physics, Higher Institute for Applied Sciences and Technology, Damascus, Syria

[2]Damascus University, Mechanical and Electrical Engineering Faculty, Damascus, Syria

Abstract: The possible energy gain in the case of two axes tracking as well as a fixed system with Equator facing tilted solar PV module with latitude angle and daily optimum slope is calculated basing on Hottel clear sky radiation model (HM) and ex-terrestrial solar radiation model (ESRM). The calculated results are compared with the data obtained from a PV system with 252 W_{peak} power module installed on a two axes solar tracker which was designed and constructed locally. The main components of the tracker are introduced. It was found that, the maximum possible energy gain calculated basing on HM and ESRM are practically identic. For example, on 25 August from 8 O'clock to solar noon, the hourly energy gain values of HM are 1.672, 1.336, 1.170, 1.098 and 1.097 while they are 1.677, 1.337, 1.170, 1.098 and 1.098 in the case of ESRM. The corresponding measured values on the same day are 1.746, 1.36, 1.16, 1.043 and 1.027. Thus, the theoretical data are consistent with the measured ones. Moreover, it was found that the tracked system is more economic feasible than latitude tilted similar one with a relative solar energy gain of 0.32%.

Keywords: Dual sun tracker; Latitude tilted solar module; Optimum tilted solar module; Energy gain; Economic feasibility.

1. INTRODUCTION

Photovoltaic energy involves the conversion of sunlight into electricity. The efficiency of converting radiant solar energy into electrical energy is the critical point that influences the choice of solar energy as a form of alternative energy. Photovoltaic (PV) systems have gained a great deal of interest in the world and these studies performed on this subject have been gaining more and more importance. The energy generated from PV modules is related with temperature, irradiance and incident angle of the solar radiation and so on. There are two ways to improve the PV technology performance. One is to use different materials or add other dopants to manufacture the PV modules. The other one is to use a tracker as the device for orienting a solar PV module toward the Sun. In order to achieve the highest conversion efficiency, the Sun light has to impinge the module surface perpendicularly. The earth not only has one year rotational motion around the Sun, but also a daily motion around its own axes. Therefore, different kinds of solar tracking could be used. Here, one can mention two types of tracking:

- Long term tracking, where the most common ones are those related to daily, fortnightly, seasonally, half-yearly and yearly tracking by determining the optimum solar collector orientation according to these periods. This kind of tracking is treated in details in and it is widely in use all over the world. Moreover, it is common practice for traditional photovoltaic (PV) modules to be installed at a fixed angle in a wide and flat area so as to generate the maximum amount of power. In this case the optimum tilt angle and azimuth angle should be determined. There are many techniques developed to determine the optimum tilt angles for different latitudes and surface azimuth angles. Soulayman and Hammoud [1] presented a modified general algorithm to optimize the tilt angle for mid-latitude zone. Stanci and Stanci [2] proposed an equation to optimize the tilt angle at latitudes from 0^o to 80^o. Benghanem [3] proposed a method to calculate the optimum tilt angle in Madinah, Saudi Arabia. Yan *et al*. [4] determined the optimum tilt angle and orientation in Brisbane, Australia. Furthermore, Optimum tilt angles for other areas such as Carbondale, Illinois, USA [5], Sanliurfa, Turkey [6], Taipei, Taiwan [7], Burgos, Spain [8], etc. have been reported. However, the fixed tilt PV system using yearly optimum tilt angle has relatively lower efficiency, but daily, weekly, fortnightly, monthly and even seasonally adjustment of the tilt angle can increase the efficiency of a solar system remarkably.
- Short term tracking, where a device for orienting a solar PV module toward the Sun during the day is used. The efficiency of a PV module can easily be increased by sun tracking systems which are investigated by many researches. The

*Address correspondence to this author at the Dept. of Applied Physics, Higher Institute for Applied Sciences and Technology, Damascus, Syria,
E-mail: soulayman1952@gmail.com

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generated power is directly proportional with the collected solar radiation in a solar system. Maximum sun power collection is possible by adjusting solar system position with respect to the Sun's location. This adjustment can be realized more easily with two axes Sun tracking systems than single ones which is cheaper and simpler to design. The tracking systems include closed and open loop control mechanisms. The PV modules are positioned by the help of photo sensors and feedback controllers. The disadvantage of the closed loop system is that the system spends more energy than the generated one in the case of quick weather changes. The open loop one is based on calculations of the seasonal weather and the sun position. The hybrid control is made up of both closed and open loop tracking systems [9].

Sun-tracking system plays an important role in the development of solar energy applications, especially for the high solar concentration systems that directly convert the solar energy into thermal or electrical energy. There are number of studies showing that tracking systems enable significant amount of solar energy compared to fixed systems. Nann [10] derived the irradiance received and the energy costs for tracking photovoltaic systems and V-trough concentrators relative to the costs of a fixed system. Tomson [11] reported increasing of seasonal energy yield by 10-20% if using the two-positional tracking system that positions collectors in the morning and in the afternoon. A very detailed review of energy gain of different trackers is done by Mousazadeh *et al*. [12] where the authors report a boost of collected solar energy by means of a tracking system in the range of 10-100% depending on different time periods and geographical conditions. However, Sun-tracking systems are quite expensive and energy intensive. An experimental study was performed by Abdallah [13] to investigate the effect of using different types of Sun tracking systems on the voltage–current characteristics and electrical power generation at the output of flat plate photovoltaics. The increment of electrical power gain was found to be up to 43.87%, 37.53%, 34.43% and 15.69% for the two axes, east–west, vertical and north–south tracking, respectively, as compared with the fixed surface inclined 32° to the south in Amman, Jordan.

Two most commonly used configurations in two-axis sun-tracking system are azimuth-elevation and tilt-roll (or polar) tracking system. The azimuth-elevation system is among the most popular sun-tracking system employed in various solar energy applications [14]. In the azimuth-elevation tracking, the collector must be free to rotate about the zenith-axis and the axis parallel to the surface of the earth. The tracking angle about the zenith-axis is the solar azimuth angle and the tracking angle about the horizontal axis is the solar elevation angle. Alternatively, tilt-roll (or polar) tracking system adopts an idea of driving the collector to follow the sun-rising in the east and sun-setting in the west from morning to evening as well as changing the tilting angle of the collector due to the yearly change of sun path [15, 16]. Hence, for the tilt-roll tracking system, one axis of rotation is aligned parallel with the earth's polar-axis that is aimed towards the star Polaris. This gives it a tilt from the horizon equal to the local latitude angle. The other axis of rotation is perpendicular to this polar-axis [17, 18]. The tracking angle about the polar-axis is equal to the sun's hour angle and the tracking angle about the perpendicular axis is dependent on the declination angle.

Lazaroiu *et al* [19] evaluated, experimentally, the performance of two photovoltaic systems tilted by 30^o: one fixed and one equipped with a single-axis sun tracker. They found that the energy gain of the tracked module is 12-20%. Eke and Senturk [20] compared the performance of two operating PV systems, one plane set to 28^o fix tilt angle which is suggested to be the yearly optimum tilt for Mugla, Turkey (latitude: 37.13^oN, longitude: 28.22^oE, altitude: 646 m) while the other operates in double axis tracking mode. The authors claimed that, the yearly energy gain of the double axis sun-tracking system, when compared to the latitude tilt fixed system, is 30.79% for Mugla climatic conditions. Dakkak and Babelli [21] reported 30% increase in injection energy to utility from one-axis solar tacking system installed in Aleppo (36.2021° N, 37.1343° E) when compared to the 35^o tilt fixed system.

In the present work a tracking system which could be either one axis or dual axis is described and the energy gain of the tracked system is evaluated with regard to horizontal, latitude tilted, daily optimum tilted, monthly optimum tilted, seasonally optimum tilted and biannually optimum tilted solar PV modules.

2. TRACKING SYSTEM

The motive behind this work is to design an automatic sun tracker, which can work as a dual axis or single axis. The function of the tracker is to make the PV module extract maximum possible amount of solar energy and convert it to electrical energy. The sun tracker should consume energy as minimum as possible. In constructing the sun tracker, see Figure **1**, four LDRs were used to achieve the optimum orientation of the PV module using two DC motors with consumption 0.3A at 12V each through the microcontroller (pic16877A). A rechargeable battery was used to store the power and to feed the tracker at the end of the day. Kipp and Zonen pyranometers were used to measure solar radiation incident on the fixed and tracked modules. Pt-100 sensors were used for measuring ambient and surface module's temperatures. Data logger is used to collect data over a period of time.

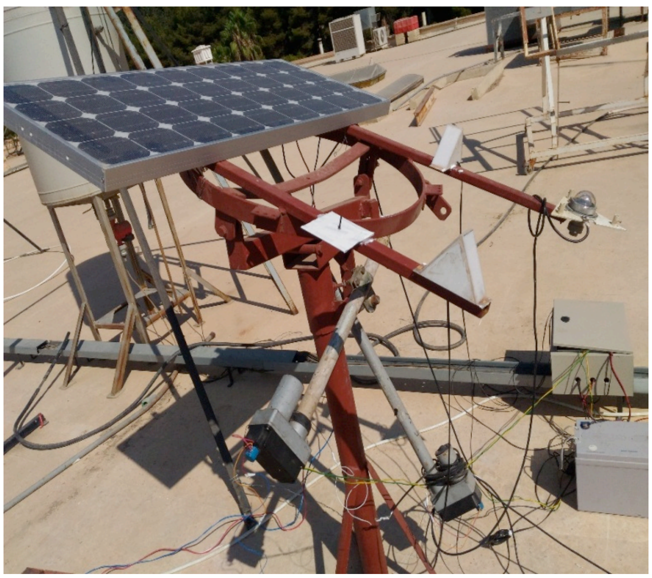

Figure 1: Dual and single sun tracker.

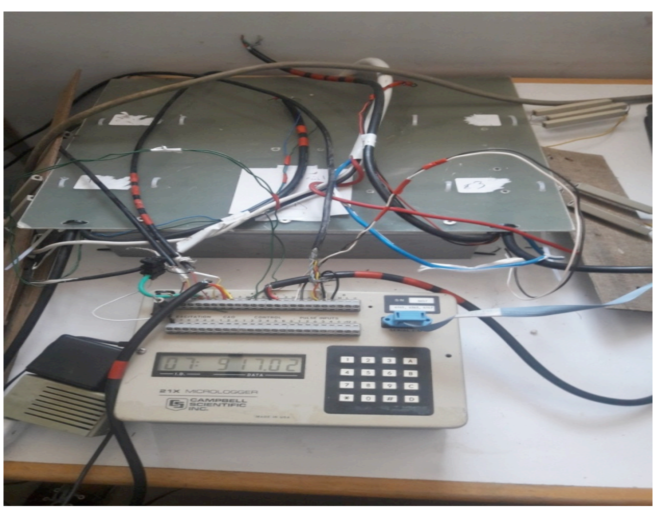

Figure 2: Data collection unit.

The measured data such as PV panel's current intensity I and voltage V, solar radiation intensity on the plane of the PV panel, PV panel's surface temperature, ambient temperature, PV panel's surface azimuth and tilt angles, are collected using an indoor arrangement where the data logger is the main component (see Figure **2**).

2.1. Solar Modules

Four PV mono-crystalline silicon modules BP 250 of 0.412 m^2 area, manufactured by BP solar, were used in the experimental setup: 1) One module is installed horizontally; 2) One module is installed on an Equator facing latitude tilted surface; 3) One module is installed on an Equator facing optimum tilted surface and 4) One module is installed on the sun tracker. The specifications of the used modules are given in the Table **1**. The module efficiency η is 12%.

Table 1: The Used PV Modules Specifications at Standard Test Conditions (STC)

	Unit	Value
P_{mpp}	W	50
V_{mpp}	V	16.6
I_{mpp}	A	3.01
V_{oc}	V	20.5
I_{sc}	A	3.15
α_1	mA/°C	221
α_2	mV/°C	-76.6
α_3	mV/°C	-81.8
α_4	mW/°C	-216.2

2.2. Experimental Setup

The experimental setup consists of a module installed horizontally, a module installed on an Equator facing latitude-tilted surface, a module installed on an Equator facing optimum tilted surface and a module installed on the sun tracker. The setup is performed with a meteorological station on the roof of the applied physics department at Higher Institute for Applied Sciences and Technology, Damascus (33.5°N, 37.5°E), Syria, where all solar radiation components are measured all over the day.

3. ENERGY GAIN

Let us consider the ideal case - the ideal instantaneous dual tracking. In this case the incidence angle satisfies the following equation:

$$\theta_i = 0^o \qquad (1)$$

Thus, the daily extraterrestrial solar radiation $H_{0,d}(n)$, incident on ideal tracked surface, on a day number n, in this case, is:

$$H_{0,d}(n) = G_s(n) S_0(n) \qquad (2)$$

where $S_0(n)$ is the maximum possible sunshine duration (day length) during the day number n. When dividing the value of the equation (2) by the value of the daily extraterrestrial solar radiation on the horizontal plane, the energy gain factor of daily instantaneous dual tracking with relation to horizontal surface could be obtained as follows:

$$R = \left[H_{0,d}\left(n, \theta_i = 0^o\right) / H_{0,d}\left(n, \theta_i variable\right) \right] = \frac{2}{15} \arccos (\,($$

$$-tg\varphi tg\delta \,/ \left[\cos\varphi \cos\delta \sin\omega_s + \frac{\pi * \omega_s}{180} \sin\varphi \sin\delta \right] \qquad (3)$$

On the other hand, the energy gain factor of daily instantaneous dual tracking with relation to Equator facing tilted surface by an angle β could be obtained as:

$$R' = \left[H_{0,d}\left(n, \theta_i = 0^o\right) / H_{0,d}\left(n, \beta\right) \right] =$$

$$\left\{ \frac{2}{15} \arccos(-tg\varphi tg\delta) / \left[\cos(\varphi - \beta) \cos\delta \sin\omega_{ss} + \frac{\pi * \omega_{ss}}{180} \sin(\varphi - \beta) \sin\delta \right] \right\} \qquad (4)$$

The hourly results of R and R', calculated using the equations (3) and (4) for different slopes, are given in Tables **2** and **3**. It is seen from Table **2** that, the dual tracking with respect to horizontal surface or with

Table 2: Energy Gain of Tracked Surface with Relation to Horizontal and different Tilted Surfaces during Winter Solstice in Damascus (33.5^{o}N, 37.5^{o}E)

hr	R	R'($\beta_{opt,d}$)	R'($\beta_{opt,m}$)	R'($\beta_{opt,s}$)	R'($\beta_{opt,b}$)	R'($\beta_{opt,y}$)	R'($\beta=\varphi$)
8.5	6.11	3.68	3.67	3.57	3.50	2.78	2.83
9.5	3.10	2.37	2.37	2.35	2.33	2.00	2.02
10.5	2.25	2.01	2.01	2.01	2.00	1.78	1.80
11.5	1.92	1.87	1.87	1.87	1.87	1.69	1.71
12.5	1.83	1.82	1.83	1.84	1.83	1.67	1.68
13.5	1.93	1.86	1.87	1.87	1.87	1.69	1.71
14.5	2.26	2.01	2.01	2.01	2.00	1.78	1.80
15.5	3.11	2.37	2.37	2.35	2.33	2.00	2.02
16.5	6.12	3.68	3.67	3.57	3.50	2.78	2.83

Table 3: Energy Gain of Tracked Surface with Relation to Horizontal and different Tilted Surfaces during Summer Solstice in Damascus (33.5^{o}N, 37.5^{o}E)

hr	R	R'($\beta_{opt,d}$)	R'($\beta_{opt,m}$)	R'($\beta_{opt,s}$)	R'($\beta_{opt,b}$)	R'($\beta_{opt,y}$)	R'($\beta=\varphi$)
5.5	46.23	13.39	14.31				
6.5	4.55	3.90	3.95	7.24	6.5	6.11	120.00
7.5	2.39	2.28	2.29	2.77	7.5	2.63	4.07
8.5	1.66	1.65	1.65	1.76	8.5	1.72	2.14
9.5	1.31	1.33	1.33	1.34	9.5	1.33	1.52
10.5	1.13	1.16	1.15	1.13	10.5	1.13	1.25
11.5	1.04	1.07	1.07	1.03	11.5	1.03	1.12
12.5	1.06	1.04	1.04	1.00	12.5	1.00	1.08
13.5	1.04	1.07	1.07	1.03	13.5	1.03	1.12
14.5	1.13	1.16	1.15	1.13	14.5	1.13	1.25
15.5	1.31	1.33	1.33	1.34	15.5	1.33	1.52
16.5	1.66	1.65	1.65	1.76	16.5	1.72	2.14
17.5	2.39	2.28	2.29	2.77	17.5	2.63	4.07
18.5	4.55	3.90	3.95	7.24	18.5	6.11	120.00
19.5	46.23	13.39	14.31				

respect to tilted surfaces with optimum daily, monthly, seasonally and biannually tilts is, practically, the same during midday hours from 11:30 to 13:30 solar time while it becomes more and more important when approaching sunrise and sunset.

Hottel [22] presented a model, with a good accuracy and simple use, to estimate the clear-day transmittance of direct solar radiation through clear sky. In this general model, with taking into account the solar zenith θ_z angle and cite altitude A the transmittance to direct solar radiation is calculated using constants and corrections for four different climate zones in the globe. The transmittance to direct or beam solar radiation through the 1962 standard atmosphere with 23 km visibility to a surface at altitude A, as presented in the clear sky radiation model, can be written as:

$$\tau_b = a_0 + a_1 \exp\left(-k / \cos\theta_z\right) \tag{5}$$

where the coefficients a_0, a_1, and k are determined using the correction factors $r_0 = a_0 / a_0^*,\ \ r_1 = a_1 / a_1^* \ \ and \ \ r_k = k / k^*$, which are given for altitudes less than 2.5 km by:

$$a_0^* = 0.4237 - 0.0082\left(6 - A\right)^2 \tag{6}$$

$$a_1^* = 0.5055 + 0.00595\left(6.5 - A\right)^2 \tag{7}$$

$$k^* = 0.2711 - 0.01858\left(2.5 - A\right)^2 \tag{8}$$

where A is the latitude of the observer in kilometers (Hottel [22] also gives equations for a_0^*, a_1^* and k^* for a standard atmosphere with 5 km visibility) and the correction factors are given in Table **4**.

Table 4: Correction Factors for Climate Types (Hottel [22]).

Climate Type	r_0	r_1	r_k
Tropical	0.95	0.98	1.02
Mid-latitude summer	0.97	0.99	1.02
Subarctic summer	0.99	0.99	1.01
Mid-latitude winter	1.03	1.01	1.00

Thus, the transmittance of this standard atmosphere for beam radiation can be determined for any zenith angle and any altitude up to 2.5 km. The clear sky beam radiation incident normally on a surface on the Earth's surface G_{cnb} (Wm^{-2}) is then:

$$G_{cnb} = \tau_b G_s \tag{9}$$

where G_s could be obtained, for nth day number in the year, from the following equation:

$$G_s = I_s * \left\{ \begin{array}{c} 1.00011 + 0.034221\, cos(B_n) \\ +0.00128 \sin(B_n) + 0.000719 cos(B_n) \\ +0.000077 * sin(B_n) \end{array} \right\} \tag{10}$$

where I_s, is the solar constant I_s = *1367 W/m^2* and $B_n = 2\pi(n-1)/365$. The clear sky beam solar radiation incident on a horizontal surface on the Earth's surface G_{cb} (Wm^{-2}) is:

$$G_{cb} = \tau_b G_s cos\theta_z \tag{11}$$

It is also necessary to estimate the clear sky diffuse radiation on a horizontal surface to get the total radiation. Liu and Jordan [23] developed an empirical relationship between the transmission coefficients for beam and diffuse radiation for clear days:

$$\tau_d = 0.271 - 0.294\tau_b \tag{12}$$

where τ_d is the ratio of diffuse radiation to the extraterrestrial radiation on the horizontal plane. The clear sky diffuse solar radiation incident on a horizontal surface on the Earth's surface G_{cd} (Wm^{-2}) is:

$$G_{cd} = \tau_d G_s cos\theta_z \tag{13}$$

The clear sky global solar radiation incident on any surface on the Earth's surface G_c (Wm^{-2}) is given by;

$$G_c = G_{cb} + G_{cd} \tag{14}$$

Then, basing on the Equations (9) to (14) it is possible to calculate the energy gain. When comparing the obtained results with those of the Equation (3) for vernal and autumn equinoxes and winter and summer solstices in Damascus, the results presented in Figure **3** are obtained.

4. RESULTS AND DISCUSSION

Basing on the equations (3) and (4) it possible to introduce instantaneous and hourly energy gain factor of R and R'. The instantaneous dual tracking energy gain with relation to horizontal surface could be obtained as follows:

$$\begin{aligned} R_1 &= \left[G\left(n, \theta_i = 0^o\right) / G_0\left(n, \theta_i variable\right) \right] \\ &= \left[\cos\varphi \cos\delta \cos\omega + \sin\varphi \sin\delta \right]^{-1} \end{aligned} \tag{15}$$

The hourly energy gain factor of instantaneous dual tracking with relation to horizontal surface could be obtained as follows:

$$R_2 = \left[H_h\left(n, \theta_i = 0^o\right) / H_{0,h}\left(n, \theta_i variable\right) \right]$$
$$= \left[\cos\varphi \cos\delta \left(\sin\omega_2 - \sin\omega_1\right) + \pi \sin\varphi \sin\delta\left(\omega_2 - \omega_1\right) / 180 \right]^{-1} \quad (16)$$

On the other hand, the energy gain factor of daily instantaneous dual tracking with relation to Equator facing tilted surface by an angle β could be obtained as:

$$R_3 = \left[H_d\left(n, \theta_i = 0^o\right) / H_d\left(n, \beta\right) \right]$$
$$= \left[\cos(\varphi - \beta)\cos\delta\left(\sin\omega_2 - \sin\omega_1\right) + \pi \sin(\varphi - \beta)\sin\delta\left(\omega_2 - \omega_1\right) / 180 \right]^{-1} \quad (17)$$

4.1. Theoretical Results

When calculting the hourly energy gain, basing on extraterrestrial method, at winter and summer solstices of tracked surface with respect to horizontal surface as well surfaces with different slopes, the results of R_2 and R_3 are given in Tables **5** and **6** respectively. It is seen from Tables **5** and **6** that, the dual tracking with respect to horizontal surface is important all over the day during winter solstice while it is negligible during midday hours

Table 5: Energy Gain of Tracked Surface with Relation to Horizontal and different Tilted Surfaces during Winter Solstice

hr	R_2	$R_3(\beta_{opt,d})$	$R_3(\beta_{opt,m})$	$R_3(\beta_{opt,s})$	$R_3(\beta_{opt,b})$	$R_3(\beta_{opt,y})$	$R_3(\beta=\varphi)$
8.5	6.11	1.66	1.67	1.72	1.75	2.21	2.17
9.5	3.10	1.30	1.30	1.32	1.33	1.55	1.53
10.5	2.25	1.12	1.12	1.12	1.12	1.26	1.25
11.5	1.92	1.03	1.03	1.02	1.02	1.13	1.12
12.5	1.83	1.00	1.00	0.99	0.991	1.09	1.08
13.5	1.93	1.03	1.03	1.02	1.02	1.13	1.12
14.5	2.26	1.12	1.12	1.12	1.12	1.26	1.25
15.5	3.11	1.30	1.30	1.32	1.33	1.55	1.53
16.5	6.12	1.66	1.67	1.72	1.75	2.21	2.16

Table 6: Energy Gain of Tracked Surface with Relation to Horizontal and different Tilted Surfaces during Summer Solstice

hr	R_2	$R_3(\beta_{opt,d})$	$R_3(\beta_{opt,m})$	$R_3(\beta_{opt,s})$	$R_3(\beta_{opt,b})$	$R_3(\beta_{opt,y})$	$R_3(\beta=\varphi)$
5.5	46.23	13.39	14.31		6.11	120.00	
6.5	4.55	3.90	3.95	7.24	2.63	4.07	4.21
7.5	2.39	2.28	2.29	2.77	1.72	2.14	2.18
8.5	1.66	1.65	1.65	1.76	1.33	1.52	1.54
9.5	1.31	1.33	1.33	1.34	1.13	1.25	1.26
10.5	1.13	1.16	1.15	1.13	1.03	1.12	1.13
11.5	1.04	1.07	1.07	1.03	1.00	1.08	1.09
12.5	1.06	1.04	1.04	1.00	1.03	1.12	1.13
13.5	1.04	1.07	1.07	1.03	1.13	1.25	1.26
14.5	1.13	1.16	1.15	1.13	1.33	1.52	1.54
15.5	1.31	1.33	1.33	1.34	1.72	2.14	2.18
16.5	1.66	1.65	1.65	1.76	2.63	4.07	4.21
17.5	2.39	2.28	2.29	2.77	6.11	120.00	
18.5	4.55	3.90	3.95	7.24			
19.5	46.23	13.39	14.31				

from 11:30 to 13:30 solar time during summer solstice and with respect to tilted surfaces with optimum daily, monthly, seasonally and biannually tilts. It becomes more and more important when approaching sunrise and sunset.

On the other hand, when comparing the results of hourly energy gain factors, calculated using the extraterresrial solar radiation method, with those, calculated using Hottel maethod, the results presented in the Figure **3** are obtained with respect to the horizontal surface. It is seen from Figure **3** that, the calculated results of hourly energy gain basing on both methods are practically the same all over the year. This means that, we can use any of these two methods for calculating the maximum possible energy gain.

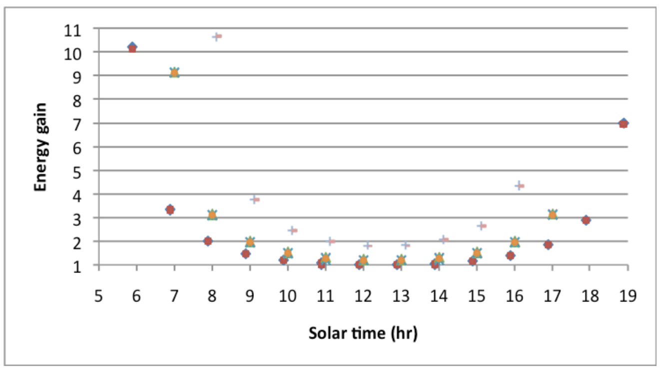

Figure 3: The calculated energy gain of tracked surface basing on Hottel [22] (summer-■, vernal-x, autumn-●, winter--) and extraterrestrial (summer-♦, vernal-▲, autumn-ж, winter-+) methods.

4.2. Experimental Results

The maximum real energy gain could be obtained by taking the ratio of the measured solar radiation intensity of tracked system to that measured on a horizontal surface. This value is influenced by climatic conditions but it rests the maximum for that day of real climatic conditions. There is another gain which related to the PV module. This gain is highly influenced by the module surface temperature. In order to distinguish between these two gains, we will denote the maximum real energy gain by radiation gain while the other one will be denoted by PV power gain.

4.2.1. Radiation Gain

When calculating and measuring the radiation gain on two clear days (day number 277 and day number 288), the results presented in Figure **4** are obtained. It is seen from Figure **4** that, the agreement between theoretical and experimental results is very good. Moreover, the tracking effect on the radiation gain is important outside the midday hours (from 11:30 to 13:30) and it becomes greater and greater when approaching sunrise and sunset.

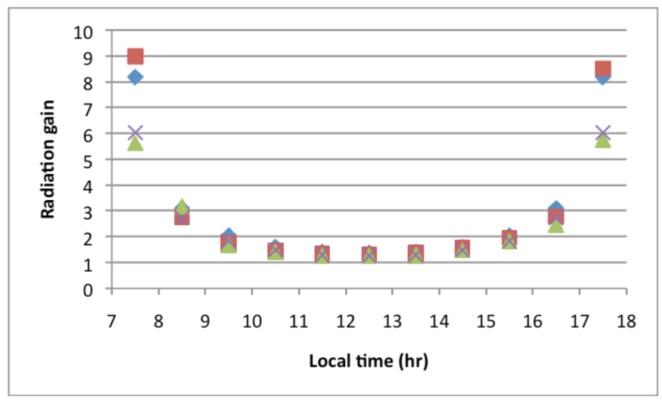

Figure 4: The calculated (x and ■) and measured (▲and ♦) radiation gain on day numbers 277 and 288 respectively.

4.2.2. PV Power Gain

In PV projects it is advised to install PV modules on a tilted surface with Equator facing orientation. The slope of the modules is sometimes chosen to be equal

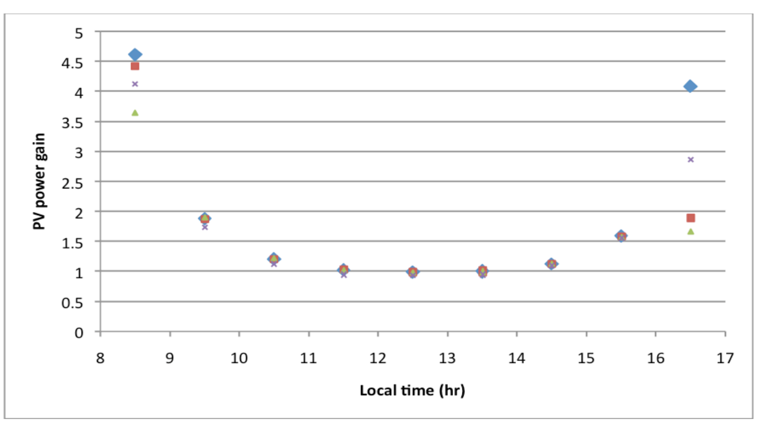

Figure 5: The measured PV power gain with respect to: daily or monthly optimum slope (▲), seasonally optimum slope (x), biannually optimum slope (■) and latitude angle slope (♦).

to the cite latitude φ or yearly optimum tilt angle $\beta_{opt,y}$. For increasing the PV system contribution, some authors advise to change the slope monthly, seasonally or biannually. Therefore, when dealing with the effect of tracking on PV system performance, it is reasonable to investigate the PV power gain with respect to the above mentioned tilted surfaces. Figure **5** shows the effect of tilt angle value of the fixed system on the PV power gain. Moreover, as solar radiation, tilt angle, ambient temperature and module surface temperature are the main affecting parameters, it is reasonable to present the above mentioned parameters side to side with the PV power gain. It is seen from Figure **5** that, the effect of tracking appears clearly outside the midday hours.

During early morning and lately afternoon hours, the PV power gain increases with changing the tilt angle of the PV modules from latitude tilted angle to optimum daily tilt angle as follows: latitude tilted angle => yearly optimum tilt angle => biannually optimum tilt angle => seasonally optimum tilt angle => monthly tilt angle => daily optimum tilt angle.

In order to have an idea about the difference between the radiation gain and the PV power gain, it is reasonable to compare these gains over a period of time and for different module tilt angle installation. When calculating the radiation and PV power gains for September and October basing on experimental data, the results presented in Table **7** are found. It is seen from Table **7** that, the radiation gain is always greater than the PV power gain. In our opinion, this phenomenon is related to the module surface temperature increase during the testing days.

Table 7: Measured Radiation and PV Power Gains

Gain	φ	$\beta_{opt,m}$	$\beta_{opt,y}$
Radiation (Sep)	1.59	1.58	1.59
PV power (Sep)	1.32	1.32	1.33
Radiation (Oct)	1.48	1.50	1.49
PV power (Oct)	1.33	1.35	1.33

On the other hand, as solar radiation, tilt angle, ambient temperature and module surface temperature are the main affecting parameters, it is reasonable to present the above mentioned parameters side to side with the PV power gain. Figure **6** presents these data for the tracked module at 277th day number. It is seen from Figure **6** that, the trends of module surface temperature increment and decrement agree well with the trends of solar radiation intensity change. The produced power of the tracked module with time up to 9:30 could be divided into three zones: two zones are with high gradient value but with different signs. These zones are early morning and lately afternoon. The intermediate zone could be characterized by a very low increment ratio and high solar radiation intensity level (>800W/m^2).

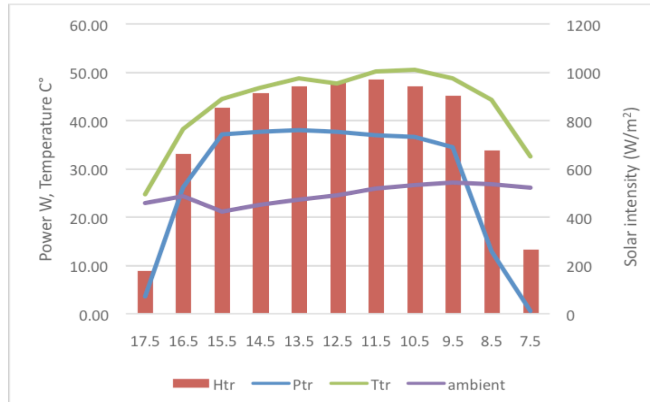

Figure 6: The measured PV power and affected parameters on day number 277. The index tr is related to tracking module.

When comparing the tracked system and fixed system, where the module is installed at Equator facing surface with tilt angle equal to $\beta_{opt,s}$ at this period ($\beta_{opt,s}$ = 56.5^o), with regard to produced power and module surface temperature, the results presented on Figure **7** are obtained. It is clearly demonstrated in the Figure **7** that, the PV power gain of the tracked is related to hours outside the midday hours (from 11:30 to 13:30). Moreover, the difference between the module surface temperature and the ambient

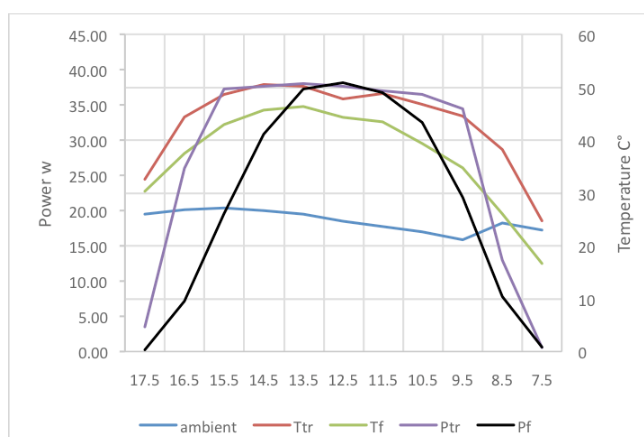

Figure 7: The measured PV powers and module surface temperatures of tracked and fixed system on day number 277. The index f is related to fixed installed module.

temperature reaches 24°C which is far enough from STC value and it affects highly on the performance of the solar PV module. Therefore, the PV power energy gain is always smaller than the radiation energy gain.

In order to use the measured data for evaluating the economic feasibility of tracking with respect to latitude tilted (LT) and monthly optimum tilted (MOT) cases in Damascus, the measured data, extended to 1 kW peak power, were compared with the results of the PVSYST software during the months September and October. For September, the PVSYST software gives the daily energy output of 4.94 kWh/day while, according to our experimental results, the daily energy output is 4.71 kWh/day.

For October, the 1 kW peak power modules installed in Damascus at monthly optimum tilt angle $\beta_{opt,m}$= 47.3, the PVSYST software gives the daily energy output of 4.30 kWh/day while, according to our experimental results, the daily energy output is 4.43 kWh/day. Thus, a good agreement is also achieved. Thus, a good agreement is achieved for both months.

5. TRACKING ECONOMIC FEASIBILITY

Basing on the above mentioned results, let us consider a fixed latitude tilted installed PV system of 1 kW peak power modules. According to PVSYST software the yearly output energy is 1588.7kWh/year. The cost of this system is 1275€. The cost of the tracked one is 1555€. The local Syrian authority is ready to buy electricity by a rate of 11.8cent €/kWh. Assuming that, the experimentally obtained energy gain, of the tracked system with respect to the latitude tilted system, is the yearly daily average value of the tracked system PV power gain, the yearly output energy is 2097.2kWh/year. With taking into consideration that, the yearly operation and maintenance (O&M) of initial investment is 0.1% for fixed system and it is 0.4% for tracked system and 25 years of life for both systems, it was found that, the net present value (NPV) is o.5 and 0.8, the internal rate of return (IRR) is 16.5% and 18.1% and the payback period (PP) is 73 months and 66 months for both systems LT and tracked system respectively.

CONCLUSIONS

Finally we can conclude that:

- The practical performance of the designed and instructed sun tracker is found to be good.
- Hottel [22] clear sky method and the extraterresrial solar radiation method are practically equivalent in calculating the maximum possible energy gain.
- Hottel [22] clear sky method and the extraterresrial solar radiation method describe well the experimental radiation gain at clear sky conditions.
- The radiation gain is always greater than the PV power gain.
- The influene of the PV module surface temperature on the PV module performance could be the main factor of the PV power gain decrement. This question well be treated in detail in the near future.
- With regard to the actual Syrian PV projects output electrical tariffs the dual axis sun tracked PV systems are economically more feasible than those fixed installed at latitude tilted angles.

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NOMENCLATURE

- α_1 Temperature coefficient of short circuit current (mA/°C).
- α_1 Temperature coefficient of open circuit voltage (mV/°C).
- α_1 Temperature coefficient of maximum power voltage (mV/°C).
- α_1 Temperature coefficient of maximum power (mW/°C).
- β Tilt angle (°) which is positive for EF case and negative for PF cases.
- $\beta_{opt,b}$ Biannually optimum tilt angle (°).
- $\beta_{opt,d}$ Daily optimum tilt angle (°).
- $\beta_{opt,m}$ Monthly optimum tilt angle (°).
- $\beta_{opt,s}$ Seasonally optimum tilt angle (°).

- $\beta_{opt,y}$ Yearly optimum tilt angle (^{o}).
- δ Solar declination angle (^{o}).
- EF Equator facing.
- G Solar radiation intensity on a tilted surface (W/m^2).
- G_o Solar radiation intensity on a horizonatl surface (W/m^2).
- G_c Clear sky solar radiation intensity (W/m^2).
- G_{cb} Clear sky beam solar radiation intensity (W/m^2).
- G_{cd} Clear sky diffuse solar radiation intensity (W/m^2).
- G_{cnb} Clear sky normal beam radiation (W/m^2).
- G_s Solar radiation intensity outside Earth's atmosphere (W/m^2).
- H Monthly average daily solar radiation on a horizontal surface (MJ/m^2).
- H_d Daily solar radiation on a tilted surface (MJ/m^2).
- $H_{d,o}$ Daily solar radiation on a horizontal surface (MJ/m^2).
- $H_{0,d}$ Daily extraterrestrial solar radiation on a horizontal surface (MJ/m^2).
- I_s Solar constant (W/m^2).
- n Day number in the year starting from January 1st.
- NH Northern Hemisphere.
- R Geometric tilt factor with respect to horizontal surface.
- R' Geometric tilt factor with respect to tilted surface.
- R_1 Instantaneous dual tracking energy gain with relation to horizontal surface.
- R_2 Hourly energy gain of instantaneous dual tracking with relation to horizontal surface.
- R_3 Daily energy gain of instantaneous dual tracking with relation to tilted surface.
- SH Southern Hemisphere.
- S_o Maximum possible sunshine duration (hr).
- T Temperature (K).
- T_a Ambient temperature (^{o}C).
- T_f Fixed cell or panel surface temperature (^{o}C).
- η Panel or cell efficiency.
- φ Latitude (^{o}) which is positive at NH and negative at SH.
- θ_i Solar rays incidence angle (^{o}).
- θ_z Solar zenith angle (^{o}).
- ω_s Sunset hour angle at a horizontal surface (^{o}).
- ω_{ss} Sunset hour angle at a tilted surface (^{o}).

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