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Determining the Optimum Tilt Solar Angle of a PV Applications at Different Sites in Jordan

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Abstract: This research comes to determine the optimum tilt angle for PV system to be considered when fixing the PV systems. The optimum tilt angle is normally close to the latitude value of the location, lots of other factors affect this. So, when designing a PV system, it is necessary to take these factors into consideration to maximize the efficiency of the PV systems. The present research investigate the main scientific parameters related to solar radiation, the models used to describe the solar radiation properties and the methods to calculate the optimum tilt angle. The optimum tilt angle for Irbid, Ajlun Amman and Zarqa is calculated by applying the appropriate methods and models. Other factors affecting the tilt angle of a PV array are reported and relevant recommendations are given.

Key words: Photo Voltaic (PV), solar radiation, tilt angle, power plant, angle, factors

INTRODUCTION

The shortage of energy resources is one of the biggest challenging problems that face the economic evolution in Jordan, the situations are worsened even by the overall regional political disorders around Jordan which resulted in cutting the energy supply lines (Egyptian gas and Iraqi oil), raising the trepidations of energy security and causing enormous losses in the sector of electricity generation.

The sustainable energy such as solar energy in the form of solar radiation has been specified as the most promising candidate of energy to replace the dependency on other energy resources. The global need for energy savings requires the usage of renewable sources in many applications. One of the renewable sources of energy is the PV solar energy (Khoury *et al*., 2016). As revealed by Hoffmann (2006), the PV solar market has shown an impressive 33% growth per year, since, 1997 till date.

Renewable energy is vastly looked at as a sustainable solution that can push the wheel of development, Jordan has a good potential for renewable and solar resources in particular (Anagreh and Bataineh, 2011; Anagreh *et al*., 2010; Jaber *et al*., 2015; Hrayshat, 2007; Nematollahi *et al*., 2016; Bataineh and Dalalah, 2013; Ammari *et al*., 2015; Habali *et al*., 2001; Anani *et al*., 1988). It has plans to increase the portion of renewable energy in its energy mix up to 20% by 2020. Solar energy and particularly, photovoltaics are among the main technologies that Jordan relies on to achieve its renewable energy targets and to meet the increasing demand on electrical energy.

The performance of PV systems at different sites around the world are studied from many researcher. Kim *et al*. (2009) study the performance and present economic analysis for two installed photovoltaic systems in different locations in Korea. The performance of a grid connected photovoltaic is monitored and studied for a long time in order to improve the PV performance (Kumar and Verma, 2016; Dhar and Dash, 2016a, b; Kow *et al*., 2016; Mohanty *et al*., 2016). Ayompe *et al*. (2010, 2011) presented the measured performance of a 1.72 kW rooftop photovoltaic system in Dublin, Ireland. Many studies presented a solution of the high energy consumption of the world countries, PV can contribute significantly to the reduction of the primary, conventional energy supply as well as to the reduction of the CO_2 emissions (Caraiani *et al*., 2015; Kumar and Madlener, 2016; Gutierrez-Martin *et al*., 2013; Adam and Apaydin, 2016; Tarroja *et al*., 2015; Aboumahboub *et al*., 2012).

Several factors can affect the Levelized Cost of Electricity (LCE) that is generated from PV source, some of these factors are installation conditions including the orientation of the PV array, distance between strings and most importantly, the tilt angle (El-Sebaii *et al*., 2010; Demain *et al*., 2013).

The tilt angle has a major impact on the solar radiation incident on a surface. For a fixed tilt angle, the maximum power over the course of a year is obtained when the tilt angle is equal to the latitude of the location. However, steeper tilt angles are optimized for large Winter loads while lower title angles use a greater fraction of light in the Summer.

The tilt angle of the solar panel affects the output of the PV array because it changes the amount of solar radiation incident on the panel (Le Roux, 2016; Hartner *et al*., 2015; Bakirci, 2012; Despotovic and Nedic, 2015; Benghanem, 2011; Khahro *et al*., 2015; Moghadam and Deymeh, 2015), therefore, installing PV panels at an optimum angle helps reducing the LCE by increasing the energy production for the same installation. Furthermore, understanding the effect of the tilt angle and the orientation helps in predicting the yield of a specific system where the panel's tilt angle or orientation is fixed such as rooftops applications in which the orientation and slope of the roof determine the tilt angle and the orientation of the panel.

The present study reviews the main scientific concepts related to solar radiation in addition to the methods used in predicting the solar radiation to be applied for obtaining the optimum tilt angle. Finally, some recommendations will be suggested regarding the optimum tilt angle for Northern part of Jordan.

MATERIALS AND METHODS

Solar radiation: In PV application design, it is a fundamental to know the amount of sunlight available at a specific site at a given time. Two common methods can characterise solar radiation which are the solar radiance (or radiation) and solar insolation. The solar radiance is an instantaneous power density in units of kW/m^2. The solar radiance varies throughout the day from 0.0 kW/m^2 at night to a maximum of about 1 kW/m^2. The solar radiance is strongly dependant on the site and local weather. Solar radiance measurements consist of global and/or direct radiation measurements taken periodically throughout the day. The solar constant can be calculated using Eq. 1:

$$G_{SG} = \delta.T^2.\frac{r_s^2}{r_{se}^2} \quad (1)$$

Solar radiation for a particular location can be given in several ways including. Typical mean year data for a particular location, average daily, monthly or yearly solar insolation for a given location, global isoflux contours either for a full year, a quarter year or a particular month, sunshine hours data, solar insolation based on satellite cloud-cover data and calculations of solar radiation. The solar constant equal to 1367 W/m^2, this value is an approximation based on the distance between the Earth and the sun which is equal to 1 AU. This value was verified experimentally and the World Meteorological Organization (WMO) chose the average value 1367 W/m^2 as the solar constant.

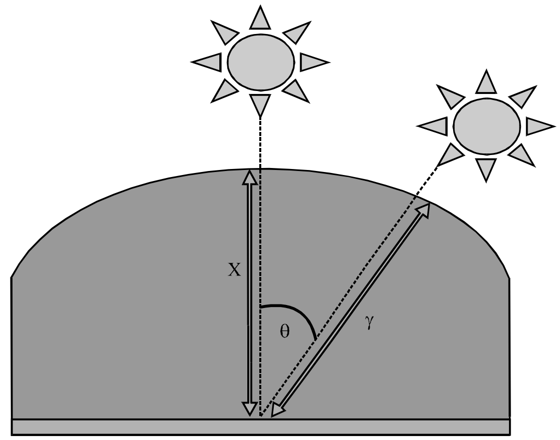

Fig. 1: The air mass represents the proportion of atmosphere that the light must pass through before striking the Earth relative to its overhead path length and is equal to Y/X

Diffusion of solar radiation: The solar radiation is subjected to several radiation attenuating effects when it travels across the atmosphere. There are two general cases of attenuating effects. Absorption and scattering (reflection is a special case of scattering). The radiation that is neither scattered nor absorbed and reaches the surface directly from the sun disk is called direct radiation while the scattered radiation that reaches the ground is called diffused radiation.

The air mass is the path length which light takes through the atmosphere normalized to the shortest possible path length (that is when the sun is directly overhead). The air mass quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust. The air mass is defined as:

$$AM = \frac{1}{\cos}(\theta) \quad (2)$$

where, θ is the angle from the vertical (zenith angle). When the sun is directly overhead, the air mass is 1 as in Fig. 1.

Solar radiation on tilted surfaces and radiance distribution over the sky: In order to calculate the incident radiation on a tilted surface, the measured value of radiation on a horizontal surface can be used in addition to the direction of the beam and the diffused radiation. The distribution of the solar diffused radiance over the sky is shown in Fig. 2. It consists of three parts, isotropic dome, circumsolar brightening and horizon brightening, the latter results from radiation reflected from the ground, thus, the horizontal brightening is a function

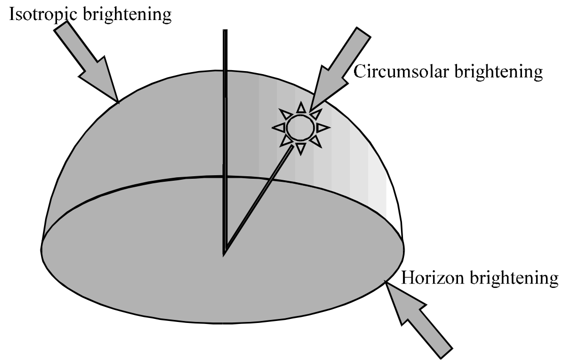

Fig. 2: Distribution of diffused radiance

of ground reflection (albedo). Clear sky diffused radiation is maximized at the horizon and decreases when moving away from the horizon and the radiance increases away from the horizon at the overcast skies.

The isotropic model can describe the overcast or cloudy sky while the anisotropic model which includes diffused sky radiation in the circumsolar and horizon brightening components of the solar radiation is more accurate in describing clear sky. Isotropic diffused solar radiation can be extracted by the following Eq. 3-8:

$$G_T = G_{T,b} + G_{T,d} + G_{T,ref} \quad (3)$$

$$G_{T,b} = G\left(\frac{\cos\beta}{2}\right) \quad (4)$$

$$G_{T,ref} = G_{T,ref}\left(\frac{\cos\beta}{2}\right) \quad (5)$$

$$G_{T,b} = G_b \times R_b \quad (6)$$

$$R_b = \frac{\cos(\varphi-\beta)\cos\delta\sin\omega_s + \left(\frac{\pi}{180}\right)\omega_s + \sin(\varphi-\beta)\sin\delta}{\cos(\varphi)\cos\delta\sin\omega_s + \left(\frac{\pi}{180}\right)\omega_s\ \sin(\varphi)\sin\delta} \quad (7)$$

$$\omega_s = \cos^{-1}(-\tan(\varphi-\beta)\times\tan\delta) \quad (8)$$

The previous equations are based on Liu and Jordan Model which is one of the simplest and earliest models. Anisotropic models should take into consideration two more components as the following Eq. 9 shows:

$$G_T = G_{T,b} + G_{T,d,iso} + G_{T,d,os} + G_{T,d,hc} + G_{T,ref} \quad (9)$$

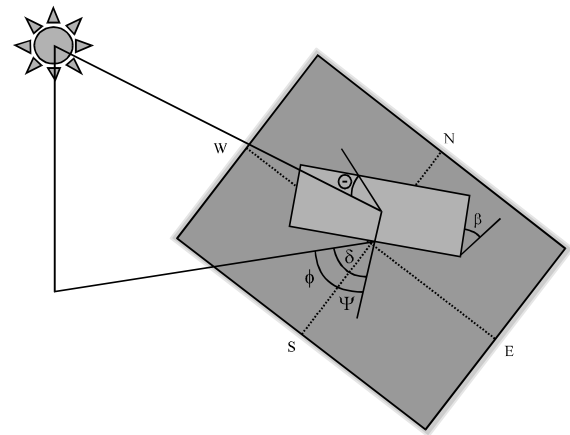

Fig. 3: Solar applications angles

Where:

G_T = The Global radiation
$G_{T,b}$ = The beam radiation
$G_{T,d,iso}$ = The isotropic component
$G_{T,d,cs}$ = The circumsolar component
$G_{T,d,hz}$ = The horizontal brightening component
$G_{T,d,ref}$ = The reflected radiation component
$G_{T,d,hz}$ = The horizontal brightening component
$G_{T,d,ref}$ = The reflected radiation component

Tilt angle calculation: Installing the PV panels with a wrong tilt angle causes a loss in the potential solar power. The optimum tilt angle determinations depend on maximizing the solar radiation falling on a sloped surface using different optimization techniques. This part shows the study of different researchers who have calculated optimum tilt angles analytically or experimentally for several of locations.

The tilt angle b of any collector is defined as the angle between the plane of the collector surface and the horizon. When b is positive, the orientation of the surface is toward the equator and when negative, it is toward the pole. The azimuth angle c is defined as the displacement angle between the projection on a horizontal plane of the normal to the collector surface and due North. The incidence angle h is the angle between the direct radiation on a surface and the normal to the surface. For maximum direct radiation, the incidence angle should be a minimum. Figure 3 shows these angles.

The assumption of standard atmosphere will certainly overestimate the incident solar radiation. However, this study mostly concentrates on the orientation of solar collectors rather than the available energy. The position of the Sun in the sky determines the direction of the direct solar radiation. Similarly, the diffused scattered component depends on how much of the surface sees the sky.

The estimation of solar radiation in most practical solar energy application can be conducted on the basis of standard atmosphere. Moreover, the daily total extraterrestrial radiation intercepted on a south facing surface, tilted by an angle b to the horizon can be expressed as (El-Kassaby, 1988):

$$I_d = \frac{24}{\pi} I_o \left[1 + 0.034\cos\left(\frac{2\pi n}{365}\right)\right] \times \left[\cos(\phi-\beta)\cos(\delta)\sin(h_{ss}) + h_{ss}\sin(\phi-\beta)\sin(\delta)\right] \quad (10)$$

Where:

$$\delta = -23.45\cos\left[(n+10.5)\frac{360}{365}\right] \quad (11)$$

And:

$$h_{ss} = \cos^{-1}\left[-\tan(\phi)\tan(\delta)\right] \quad (12)$$

Here, ϕ, β, δ and h_{ss} are latitude of the location, tilt angle, declination angle and sunset hour angle, respectively.

For optimum tilt angle at that particular day ($\beta_{opt,d}$), the derivative of I_d with respect to β must equal zero, i.e., $dI_d/d\beta = 0$ from which we find:

$$\beta_{opt,d} = \phi - \tan^{-1}\left[\frac{h_{ss}}{\sin(h_{ss})}\tan(\delta)\right] \quad (13)$$

It is not practical to design a solar collector for which the tilt angle changes every day. However, it may be possible to change it once a month. Therefore, the total monthly radiation can be obtained as:

$$I_m = \sum_{n=n1}^{n=n2} I_d$$

Where:

m = The month number

n1 and n2 = The first and the last days of the month as counted from January, respectively

For optimum tilt angle $\beta_{opt,m}$ at a particular period of time Δn, the derivative of I_d with respect to β must be equal to zero from which we find:

$$\beta_{opt,d} = \phi - \tan^{-1}\frac{x}{y} \quad (14)$$

$$X = \sum_{n=n1}^{n=n2} \frac{24}{n} I_o \left[1 + 0.034\cos\left(\frac{2\pi n}{365}\right)\right]\sin(\delta)\, h_{ss}$$

$$Y = \sum_{n=n1}^{n=n2} \frac{24}{n} I_o \left[1 + 0.034\cos\left(\frac{2\pi n}{365}\right)\right]\cos(\delta)\sin(h_{ss})$$

It is worth in this regard to mention that the monthly-averaged daily mean sunset hour angle for the tilted surface is given by:

$$h_{ss} = \min\left[\cos^{-1}(-\tan\phi\tan\delta), \cos^{-1}(-\tan(\phi-\beta)\tan\delta)\right] \quad (15)$$

where, "min" means the smaller of the two items in the bracket.

RESULTS AND DISCUSSION

Optimum solar angle calculation: To answer the question "is it worth changing the tilt angle once a month?" the set of Eq. 10-14 is used to obtain the optimum tilt angle for a month. Table 1 and Fig. 4 show the results obtained for different sites where it is to be noted that the negative values of $\beta_{opt,m}$ are considered zero. This is due to the fact that it is impractical to design a solar collector with negative tilt angles. A positive value sign indicates that the solar collector is directed toward the South, i.e., South facing. The orientation of a solar collector is determined by the azimuth angle. Three locations show that they have the same optimum tilt angle over all months which are Ajlun Amman and Zarqa while the last selected site shows different optimum angle over approximately all months. The maximum tilt angle for all selected sites was in June and the lowest was in December.

Since, changing the tilt angle to its daily and monthly optimum values throughout the year does not seem to be practical another possibility such as

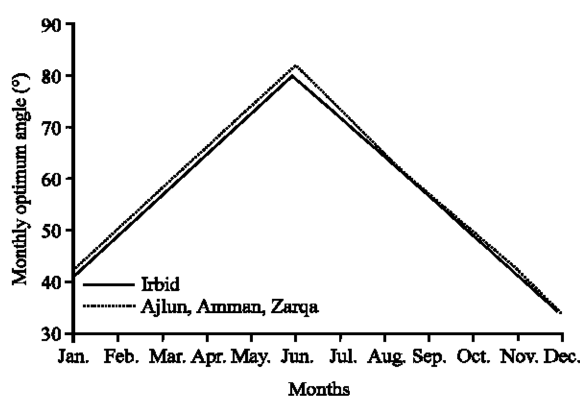

Fig. 4: The variation of monthly optimum tilt angle

Table 1: The monthly optimum tilts angle

Sites	Months (°) Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Irbid	41	49	57	65	73	80	73	65	57	49	41	34
Ajlun	42	50	58	66	74	82	74	66	58	50	42	34
Amman	42	50	58	66	74	82	74	66	58	50	42	34
Zarqa	42	50	58	66	74	82	74	66	58	50	42	34

Table 2: The seasonally and yearly optimum tilts angle

Sites	Months (°) Winter	Spring	Autumn	Summer	Years
Irbid	34	57	57	80	57
Ajlun	34	58	58	82	58
Amman	34	58	58	82	58
Zarqa	34	58	58	82	58

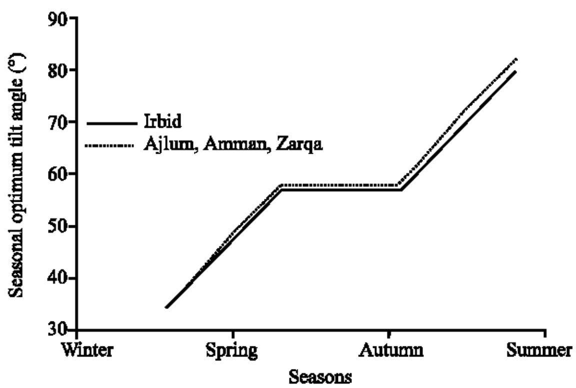

Fig. 5: The variation of seasonal optimum tilt angle

changing the tilt angle once in a period of 3 months (i.e., seasonally) was considered. The calendar year has been divided into four parts (seasons), Autumn (September-November), Winter (December-February), Spring (March-May) and Summer (June-August). The fixed tilt angle for each season was evaluated. The seasonal and yearly variation of optimum angle $\beta_{opt,s}$ for the main zones is listed in Table 2. Moreover, the seasonal variation of optimum angle $\beta_{opt,s}$ for the is plotted in Fig. 5 and 6.

Solar irradiance: The power incident on a PV module depends not only on the power contained in the sunlight but also on the angle between the module and the Sun. When the absorbing surface and the sunlight areperpendicular to each other, the power density on the surface is equal to that of the sunlight (in other words, the power density will always be at its maximum when the PV module is perpendicular to the Sun). However, as the angle between the sun and a fixed surface is continually changing, the power density on a fixed PV module is less than that of the incident sunlight.

Solar irradiance is a measure of how much solar power you are getting at your location. This irradiance varies throughout the year depending on the seasons. It also, varies throughout the day, depending on the position of the Sun in the sky and the weather.

In this research, the solar irradiance is calculated based on a panel with South facing directly direction. The tilt angle is consider to make the solar irradiance calculations for this research the solar irradiance is calculated based on angle with several positions which are Vertical Surface angle (VS), Optimal Year round angle (OY), Adjusted angle through the Year (AY), Best Winter angle (BW), Best Summer angle (BS), Flat Surface angle (FS). Figure 5 shows the panel faced at several tilt angles at a selected site (Irbid) from the investigated sites.

Amount of solar radiation striking a surface normal (perpendicular) to the sun's rays at the top of the Earth's atmosphere:

$$G_{ON} = G_{SC}\left(1+0.0033\cos\left(\frac{360n}{365}\right)\right) \quad (16)$$

Where:

G_{on} = The extraterrestrial normal radiation (kW/m^2)
G_{sc} = The Solar Constant (1.367 kW/m^2)
n = The day of the year (a number between 1 and 365)

The solar irradiance was calculated and tabulated in Table 3 and presented in Fig. 7, the result shows that the maximum solar irradiance was during June at the Adjusted angle through the Year (AY) and Flat Surface angle (FS) with an average of 7.75 kWh/m^2/day. The minimum solar irradiance was in December at Flat Surface angle (FS) with an average of 2.45 kWh/m^2/day. The result shows a similarity in the solar irradiance calculation between the four selected sites which leads to assumption that the PV systems can research anywhere in Jordan with approximately same performance and ability.

Table 3: Solar irradiance for all sites at different tilt angles

Variables	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Irbid												
VS	3.36	3.44	3.48	2.97	2.49	2.22	2.34	2.88	3.75	4.17	3.80	3.34
OY	3.75	4.33	5.32	6.01	6.55	6.76	6.75	6.64	6.38	5.47	4.31	3.58
AY	3.95	4.42	5.32	6.14	7.04	7.74	7.36	6.97	6.38	5.57	4.54	3.86
BW	3.95	4.42	5.20	5.58	5.73	5.74	5.81	5.98	6.14	5.56	4.54	3.82
BS	3.34	4.01	5.16	6.14	7.04	7.45	7.36	6.94	6.28	5.09	3.85	3.15
FS	2.66	3.40	4.67	5.90	7.16	7.74	7.58	6.85	5.76	4.33	3.08	2.46
Ajlun												
VS	3.33	3.41	3.45	2.95	2.47	2.19	2.31	2.86	3.72	4.14	3.76	3.31
OY	3.73	4.32	5.30	6.00	6.54	6.75	6.74	6.62	6.37	5.46	4.29	3.56
AY	3.93	4.40	5.30	6.14	7.04	7.75	7.35	6.96	6.37	5.54	4.51	3.83
BW	3.93	4.40	5.18	5.56	5.71	5.72	5.79	5.96	6.11	5.53	4.51	3.80
BS	3.33	4.00	5.15	6.13	7.04	7.44	7.35	6.94	6.28	5.08	3.84	3.14
FS	2.66	3.40	4.67	5.90	7.16	7.75	7.58	6.85	5.76	4.33	3.08	2.46
Amman												
VS	3.30	3.39	3.43	2.92	2.45	2.17	2.29	2.83	3.69	4.10	3.72	3.27
OY	3.71	4.30	5.29	5.99	6.53	6.73	6.72	6.61	6.35	5.44	4.27	3.54
AY	3.91	4.39	5.29	6.13	7.03	7.75	7.35	6.95	6.35	5.52	4.48	3.81
BW	3.91	4.38	5.16	5.54	5.69	5.70	5.77	5.94	6.09	5.51	4.48	3.77
BS	3.32	3.99	5.15	6.13	7.03	7.43	7.35	6.93	6.27	5.07	3.83	3.13
FS	2.66	3.40	4.67	5.90	7.16	7.75	7.58	6.85	5.76	4.33	3.08	2.45
Zarqa												
VS	3.44	3.41	3.44	2.90	2.44	2.18	2.30	2.83	3.68	4.11	3.68	3.32
OY	3.84	4.32	5.30	5.90	6.40	6.74	6.73	6.57	6.32	5.44	4.23	3.59
AY	4.05	4.41	5.30	6.03	6.89	7.75	7.35	6.91	6.32	5.53	4.43	3.86
BW	4.05	4.41	5.17	5.46	5.59	5.71	5.77	5.91	6.06	5.52	4.43	3.82
BS	3.42	4.01	5.15	6.03	6.89	7.43	7.35	6.89	6.24	5.07	3.79	3.16
S	2.73	3.41	4.67	5.82	7.01	7.75	7.58	6.81	5.73	4.33	3.05	2.47

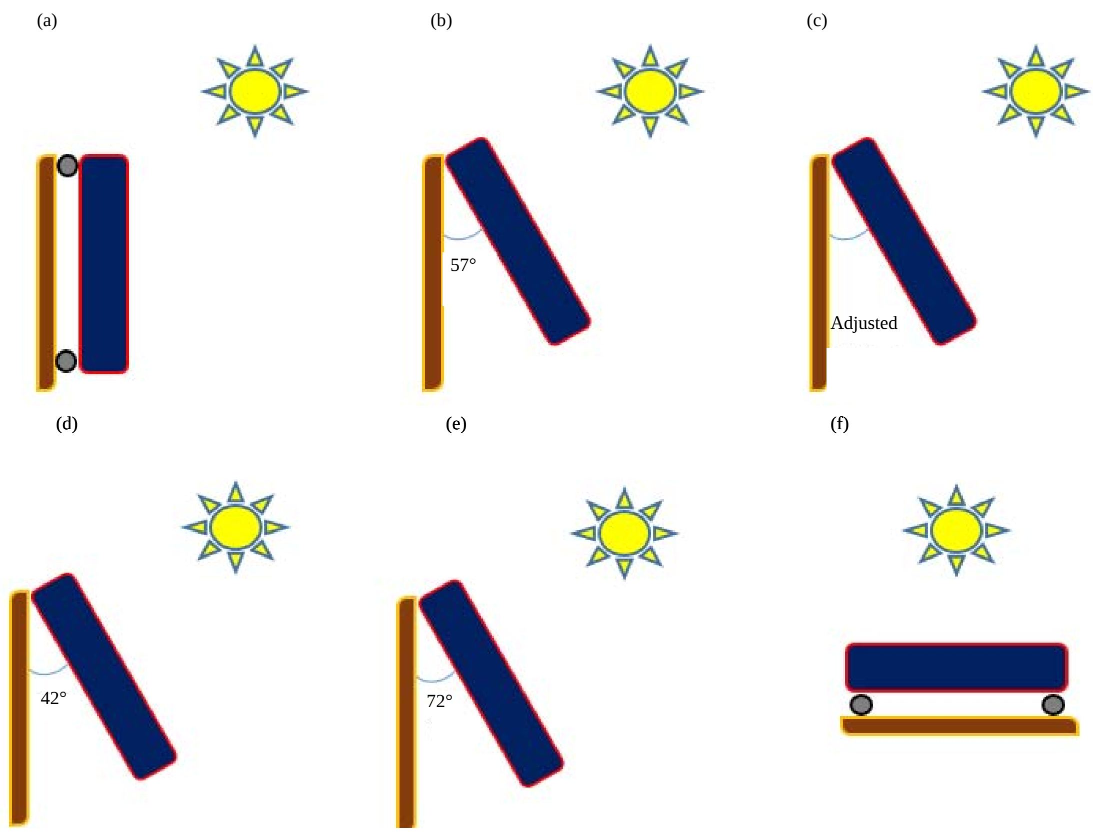

Fig. 6: Solar irradiance at different angles for Irbid; a) Virtual surface; b) Optimal year round; c) Adjusted throughout the year; d) Best Winter performance; e) Best Summer performance and f) Best Summer performance

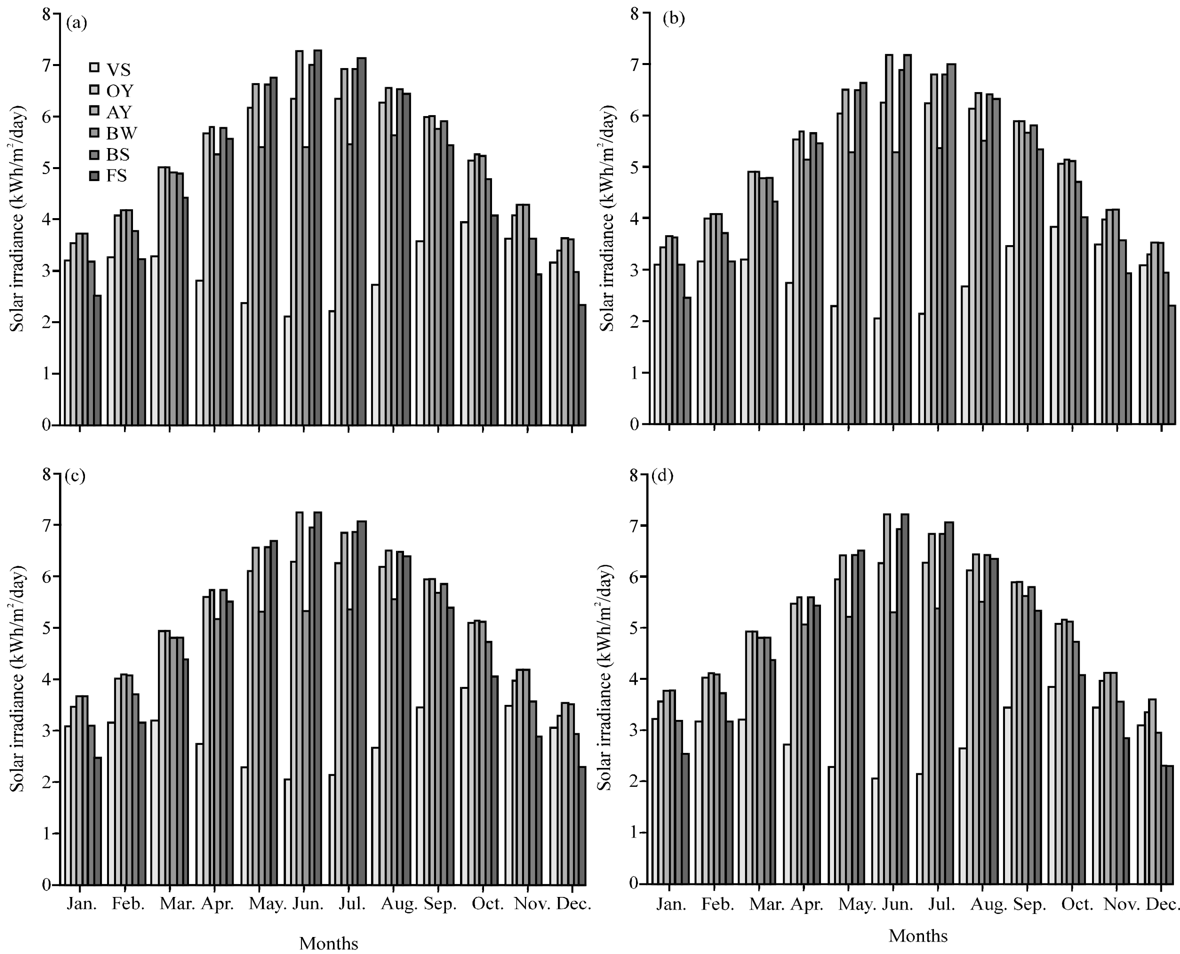

Fig. 7: Solar irradiance for; a) Irbid; b) Ajlun; c) Amman and d) Zarqa at different tilt angles

CONCLUSION

The optimum tilt angle is different for each months of the year. The collected solar energy will be greater if we choose the optimum panel tilt for each month (AY). The results show that the average optimum tilt angle at Irbid, Ajlun Amman and Zarqa for the Winter months is 34. And for the Summer months is 81.5 in average. So, the yearly average tilt panel is 58. The loss of energy when using the yearly average fixed angle is around 12% compared with the optimum tilt for each month. It can be concluded that a yearly average fixed tilt can be used in many general applications in order to keep the manufacturing and installation costs of collectors low. For higher efficiency, the collector should be designed such that the angle of tilt can easily be changed at least on a seasonal basis if not monthly. Alternatively, solar tracking systems can be used in industrial installations where higher efficiency is required. The corresponding researcher states that there is no conflict of interest.

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