Study of Energy Gains by Orientation of Solar Collectors in Baghdad City

Hussein Mohammed Taqi Al-Najjar – Lecturer

Department of Energy Engineering – College of Engineering –University of Baghdad

Email:quality_electric61@yahoo.com

ABSTRACT

Firstly, in this study, a brief updated description and applications of different solar collectors used in renewable energy systems for supplying electric and thermal energy was presented. Secondly, an attempt was made to utilize tilting orientation of solar collector for maximizing collector energy with time in respect to horizontal orientation. For energy calculation, global solar radiation was used since they are directly related. For that purpose, field measurements of half-hourly radiation on two flat panels of tilting and horizontal orientations were carried out throughout 8-month period under local climate of Baghdad. Then, energy gain and radiation level averages were calculated based on the field radiation data using Excel programming. The tilting orientation was found to be more effective for the winter months with significant energy gains of larger than 40% and maximum gain of 58%. On the contrary, the radiation levels on collector were lower during winter months. Finally, for clear sky condition, the average solar radiations for tilting and horizontal orientations of collector were of 910 W/m^2 and 713 W/m^2 respectively.

Key words: solar collector, PV, thermal, tilting orientation, horizontal orientation, energy gain.

دراسة أرباح الطاقة من توجيه المجمعات الشمسية في مدينة بغداد

حسين محمد تقي النجار – مدرس

قسم هندسة الطاقة - كلية الهندسة – جامعة بغداد

الخلاصة

في هذه الدراسة تم أولا وصف موجز ومحدّث لأنواع وتطبيقات المجمعات الشمسية في أنظمة الطاقة المتجددة لتجهيز الطاقة الكهربائية والحرارية. وثانياً، أستخدم توجيه الأمالة لزيادة طاقة المجمع مع الزمن مقارنة مع التوجيه الأفقي. لحساب الطاقة، أستخدم الأشعاع الشمسي الكلي لأنهما متناسبين بصورة مباشرة. لهذا الغرض، تم أجراء القياسات الحقلية للأشعاع كل نصف ساعة على لوحين مستويين ذوا توجيه الأمالة والأفقي ولمدة ثمان شهور وفق البيئة المحلية لمدينة بغداد. ثم، تم حساب معدلات ربح الطاقة ومستوى الأشعاع وفق البيانات الحقلية بطريقة برمجة أكسل. وجد بأن توجيه الأمالة ذو فعالية أكبر في شهور الشتاء بأرباح طاقة أعلى من 40% وأقصى ربح 58%. وعلى العكس، فأن مستويات الأشعاع للمجمع كانت أوطأ في شهور الشتاء .أخيرا، في ظروف السماء الصافية، كان معدل الأشعاع الشمسي لتوجيه الأمالة والأفقي للمجمع هو 910 واط/م^2 و713 واط/م^2 على التوالي.

كلمات رئيسية: مجمع شمسي، كهروضوئي، حراري، توجيه الأمالة، توجيه أفقي، ربح الطاقة.

1. INTRODUCTION

Renewable energy systems utilizing solar collectors, including photovoltaic (PV) or thermal panels, are being one of the important technologies in supplying electric, heating and cooling energy for power systems and buildings, **Herrando, et al., 2014**, **Fang,** and **Li, 2013**, **Cao, et al., 2014**.

In fact, in 2007, global renewable power accounted for 18% of the total power generation in the world. The total operating capacity of solar PV power and solar thermal power was 10 GW and 425 MW respectively. The world solar heating and cooling capacity was 125 GW_{th} , **REN21, 2013**.

The amount of output energy of a solar collector depends on several parameters such as design, material and structure of collector, local meteorological condition, geographic location, time and the relative orientation of the collector to both the sun and the sky. The latter parameter directly affects the energy input to the associated solar energy system, **Lubitz, 2011**. Different orientation mechanisms of solar collectors are available such as: adjusting of tilt angle, azimuth angle, both, inclined axis or other. Adjustment can be made continuously, daily or per other selected time step. The effectiveness of an orientation mechanism can be evaluated by calculating the corresponding energy gain as compared to a reference collector. Different studies have been carried out around the world to evaluate various orientation methods of PV and thermal collectors under site-related conditions.

In Saudi Arabia, **Ahmed, et al., 2015** found by analytical modeling of an on-site PV system in Dhahran city, that the yearly energy gain of continuous and monthly tilting was 43% and 19% respectively as compared to horizontal system.

For main Syrian zones, **Skeiker, 2009** used a mathematical model to estimate the incident solar radiation on a solar collector. The results revealed that the solar gain of 12 times tilting in a year was 30% with respect to horizontal collector.

In Jordan, **Al Tarabsheh, et al., 2012** simulated the solar radiation, neglecting diffuse and reflected components, near the Hashemite University for 10% efficiency PV modules using the Meteonorm 5.0 software. The annual energy gain of hourly tilting was calculated as 5.87% compared to fixed PV modules.

At university of Bechar Algeria, **Rebhi, et al., 2010** studied the performance of a prototype system for permanent orientation of PV module. An efficiency gain of 27.48% was found for a particular day compared to fixed system.

Khorasanizadeh, et al., 2014 established a diffuse model to calculate the solar gain of monthly adjustable tilt–angle collector in Tabass city, Iran. The yearly gain was found to be 23.15% compared to horizontal collector.

For different areas in china, **Li, et al., 2010** suggested a mathematical procedure based on solar geometry to estimate the annual collectible radiation on solar panels. The gain using an orientation method about inclined axis was found to be 20-30% compared to fixed panels.

Chang, **2009** investigated the yearly gains for solar collectors in Taiwan from observed data of global radiation during ten years (1990-1999). The gain using single-axis adjustment was found to lie between 14.3 to 25.3% as compared to fixed collector.

In Malaysia, **Sunderan, et al., 2011** utilized monthly average of daily solar data for estimating the total radiation on PV panel. The annual energy gain was calculated to be 6.4% for monthly tilting as compared to horizontal PV panel.

For the European continent, **Huld, et al., 2010** presented a method for estimating energy output from PV systems using solar radiation and temperature data bases with PV performance models. The gain of inclined orientation compared to fixed system was approximately 30% in southern Europe, about 20-25% in central Europe and up to 50% in northern Scandinavia.

The present work aimed firstly to present a brief updated description of solar collector types and applications. Secondly to find the energy gains and radiations level by orientation of solar collectors under local climate condition of Baghdad city. Calculations are to be based on field measurements of half-hourly global solar radiations on tilting and horizontal dummy panels for 8-month period: October to May.

2. TYPES OF SOLAR COLLECTORS, Duffie, and Beckman, 2013, Kalogirou, 2013, Twidell, and Weir, 2005.

A solar collector transforms solar incident energy of wavelengths 0.3-3.0 µm into some other energy form: thermal, electric or both according to the optical characteristics of the energy-absorbing surface of the collector, called receiver which could be of flat, concave or convex geometry. In this respect, solar collectors can be classified according to the form of its output energy.

On the other hand, solar collectors can be classified according to the level of incident radiation on the receiver. A concentrator is added to the collector structure such that to direct the solar radiation onto the receiver. The concentrator could be reflectors or refractors of different geometries: two-dimensional (linear) such as flat or cylindrical or three-dimensional (circular). Consequently, a concentrating collector can operate at higher solar radiation level. In this case, the receiver will have smaller area compared to non-concentrating collector.

An important characteristic parameter for concentrating collector is its concentration ratio C. It is the ratio of the aperture area A_a of the concentrator to the area of the receiver A_r, which is approximately the factor by which the solar radiation on the receiver is increased from its normal level that is of an average maximum 1.1kW/m^2 as in non-concentrating collectors.

The input energy to the collector, E_i (kWhr) is

$$E_i = G_{ir}\, A_r \qquad (1)$$

Where: G_{ir} is the incident solar radiation (kWhr/m^2) on the receiver. Thus, the variable parameter for the input energy is the solar radiation. The G_{ir} is related to the incident solar radiation on the aperture G_{ia} (kWhr/m^2) by the concentration ratio C as:

$$G_{ir} = C \, . \, G_{ia} \tag{2}$$

Where

$$C = \frac{A_a}{A_r} \tag{3}$$

The G_{ia} is also called the global incident radiation. Different mathematical models can be found in literature as in **Sen, 2008** for estimating the radiation components of G_{ia} including the view factors of a particular collector orientation for each radiation component. The amount of the absorbed energy per unit area of the receiver S_r (kWhr/m^2) depends on the optical properties of the collector:

$$S_r = \alpha \, . \; G_{ir} \tag{4}$$

Where α is a lumped parameter for collector optical characteristics. A different α is associated with each radiation component. According to the specific design and structure of the solar collector, part of the absorbed energy is transformed into useful output energy E_o (kWhr) as thermal, electric or both. The types of solar collectors will be explained according to above classifications as follows:

2.1 Solar Thermal Collectors, Kalogirou, 2004, Mills, 2004.

In this type of collectors, the receiver is a black absorber surface which could be provided with glass cover to reduce convection and radiation losses to the atmosphere. Also, the receiver might be enclosed in an evacuated space to obtain low loss coefficients. Absorbed thermal energy by the receiver is transferred by forced convection to working fluid, using tubes or ducts, as useful output energy.

Non-concentrating thermal collectors can deliver thermal energy at moderate temperatures up to 100^{o}C above ambient. The major applications of these collectors are in water heating, industrial process heat and air conditioning for buildings (space heating and cooling).

For applications of higher energy-delivery temperatures up to 1500^{o}C, concentrating thermal collectors are used. Depending on its particular geometry, higher concentration ratios provide higher solar radiation, lower heat losses and higher working temperatures. Concentration ratio of the order of 10^5 can be obtained. The major applications of such collectors are in solar power systems where steam is utilized to convert thermal energy to mechanical and then to electrical energy. Different configurations of thermal collectors can be constructed as shown in **Fig.1** and **Fig.2**.

2.2 Solar PV Collectors, Tiwari, and Dubey, 2010.

For this type of collectors, the receiver is photovoltaic (PV) cell which is a junction semiconductor that converts part of solar radiation directly to electric energy by photoelectric effect. The other part will be converted into thermal energy. PV collector is an array of identical PV modules that are arrayed in series and parallel to obtain the desired current and voltage for the load to which it is connected. A power conditioning equipment is usually needed to match the operating characteristic of the PV collector with that of the load. For ac loads, inverters of desired frequency will be required. **Fig.3** shows the electric circuit for PV collector.

Obviously, the electric energy is removed by external circuit (the electric load). On the other hand, the thermal energy should be removed by some heat transfer mechanism so PV cell will operate at lowest possible temperature, otherwise its electrical efficiency will be reduced.

For non-concentrating PV collectors, the incident solar radiation is of normal level. Thus, output power per unit area of collector is limited. Thermal losses may be removed by natural convection. The application of such collectors is in on-site or on-grid power systems, **Al-Najjar, 2013**.

The high costs of PV cells led to consideration of operation of these cells at high levels of solar radiation. Concentrating PV (CPV) collectors use multi-junction PV cells of flat or concave geometry with concentration ratios up to 400. Cell materials must be able to withstand high operating temperatures. In addition, sufficient cooling of PV collector should be assured. Application of such collectors is in on-grid power systems as a promising technology for future power. Typical configurations of PV collectors are shown in **Fig.4** and **Fig.5**.

2.3 Solar Photovoltaic-Thermal Collectors (PVT)

As explained above, PV receiver produces combination of electric and thermal energy. Thus, a PVT collector is a hybrid solar device. The thermal energy is treated as in thermal collectors. PVT collectors could be non-concentrating or concentrating (CPVT). In both types, the electrical energy can be used for supplying power systems, whether off-grid or on-grid; while the thermal energy can be utilized for water heating, air conditioning or for thermal power systems, **Tiwari,** and **Dubey, 2010**, **Amori,** and **Al-Najjar, 2012**.

3. ORIENTATION OF SOLAR COLLECTORS

As explained, different orientations of solar collector changes the energy input to the associated solar energy system and in turn changes its energy output. In fact, collector orientation aims to get maximum possible incident radiation with time such that to maximize output energy.

The orientation of a solar collector is specified by two angles: the tilt angle β and the azimuth angle γ; see **Fig.6**. The figure shows a non-concentrating collector however it also applies to a concentrating collector. Each of the two angles can be adjusted using different mechanisms within some selected time step such as continuously, daily, weekly, monthly and so on. Three mechanisms of collector orientation are explained below, **Duffie,** and **Beckman, 2013**, **Kalogirou, 2013**.

Tilting mechanism:

For continuous tilting, the tilt angle is adjusted to optimum β_o according to:

$$\beta = \theta_z = \beta_o \tag{5a}$$

Otherwise, for tilting in daily, weekly, monthly basis… and so on, the tilt angle is:

$$\beta = |\phi - \delta| = \beta_o \tag{5b}$$

The azimuth angle is determined by:

$$\gamma = \begin{cases} 0° & if \quad \phi - \delta > 0 \\ 180° & if \quad \phi - \delta \leq 0 \end{cases} \tag{6}$$

Where the zenith angle θ_z is calculated by:

$$cos\theta_z = cos\phi \cos\delta \cos\omega + sin\phi \sin\delta \tag{7}$$

The hour angle ω in degrees is found as:

$$\omega = 15°(t_s - 12) \tag{8}$$

Solar time in hours t_s is approximately equal to local time for this study. Where ϕ is the site latitude and δ is the solar declination angle and is given by:

$$\delta = 23.45° \sin\left[\frac{360}{365}(284 + n)\right] \tag{9}$$

where n is the nth day of the year.

Azimuthal mechanism:

The tilt angle is

$$\beta = constant \tag{10}$$

Which needs to be optimized such that it gives maximum energy over the whole period of evaluation.

The azimuth angle is adjusted to optimum γ_o according to:

$$\gamma = \gamma_s = \gamma_o \tag{11}$$

The sign of γ is the same as that of ω as given by Eq. (8). The solar azimuth angle γ_s is found by:

$$\cos\gamma_s = \frac{cos\theta_z \ sin\phi - \sin\delta}{sin\theta_z \ cos\phi} \tag{12}$$

Two-angle mechanism:

Both angles are adjusted to optimum β_o and γ_o as:

$$\beta = \theta_z = \beta_o \tag{13}$$

And

$$\gamma = \gamma_s = \gamma_o \tag{14}$$

To evaluate a certain orientation mechanism for a given solar collector, the corresponding percentage gain $g\%$, which is the energy increase in respect to the energy of a reference orientation, is calculated as:

$$g\% = (r - 1) \times 100 \quad (15)$$

Where r is energy ratio given by:

$$r = \frac{collector\ energy\ of\ an\ orientation\ mechanism}{collector\ energy\ of\ a\ reference\ orientation} \quad (16)$$

The energy in the ratio r above could be input energy or output energy of the collector over a specified time. Output power could also be used. The denominator of Eq. (16) represents the reference for energy comparison which could be of horizontal or other fixed orientation. For horizontal reference, the two angles are:

$$\beta = 0\ \ and\ \ \gamma = 0 \quad (17)$$

The gain equation, Eq. (15), is based on half-hourly results of the present study. Then, as required, daily, monthly and annual average gains can be obtained.

4. EXPERIMENTAL WORK

The experimental study presented in this paper involves four objectives as follows:

Firstly, the solar collector under study is a non-concentrating type. Thus, aperture and receiver of the collector are identical and the concentration ratio C, Eq. (3), is unity.

Secondly, energy gains are to be found using the input energy to solar collector rather than its output energy. Thus, for a given area A_r of the receiver, the energy ratio r of Eq. (16) for gain calculation will be the ratio of the corresponding incident solar radiations as can be found using Eq. (1). In this respect, solar collectors will not discriminate between thermal and PV collectors.

Thirdly, the orientation of collector that to be evaluated for gain is of tilting mechanism with weekly adjustment as described by Eq. (5b) and Eq. (6).

Fourthly, the calculated gains are to be obtained as compared to the horizontal orientation of collector as described by Eq. (17).

For the purpose of applying above issues, two structures of wooden panels are fabricated. One is of adjustable tilt angle β such that it can be set manually, at each day of experiment, to optimum value β_o according to Eq. (5b) with site latitude ϕ equal to 33° for Baghdad city. However, the panel is fixed at zero azimuth angle γ according to Eq. (6) since $\phi > \delta$ as given by Eq. (9) for all n. Thus, this panel represents the collector orientation that to be evaluated; see **Fig.7a**.

The other panel is fixed at horizontal orientation, i.e. of zero tilt angle and zero azimuth angle as given by Eq. (17). This panel represents the reference collector for gain calculation; see **Fig.7b**.

Field measurements of global solar radiation on each of the two collector orientations of **Fig.7** are carried out simultaneously at every half-hour from 8:00 am – 4:00 pm. This work is conducted in eight months (17 October 2013 to 15 May 2014) on a weekly basis at the solar laboratory of energy engineering department at Baghdad/Al-Jadriya. These half-hourly data are used to find daily and monthly averages of energy gains of the solar collector. Different climate conditions were encountered, during the 8-month period, such as sunny, windy, cloudy and rainy. This will definitely affect gain values.

5. RESULTS AND DISCUSSION

The whole experimental data obtained for a period of eight months were tabulated in Excel sheets according to half-hour measurements of each day of experiment. Excel sheets were programmed to calculate the energy gain from the measured data for the two orientations, tilting and horizontal, of the solar collector. First, the individual gain per each half-hour was calculated by Eq. (15). Then, daily average gains were found. Finally, monthly average gain for each of the eight months, October to May, was determined. In addition, Excel sheets calculate daily and monthly averages of solar radiation for each of the two collector orientations.

In respect to daily average gains within the whole 8-month period, a maximum value of 82% was obtained on 27 December 2013 with half-hourly variation as shown in **Fig. 8**. In fact, during this month the solar declination δ is at its maximum negative $\approx$ -23^{o}. Thus, tilting collector is set at maximum angle of β_o = 56^{o} as compared to zero angle of the horizontal collector. This will give maximum energy gain. **Fig. 8** indicates larger gains at hours far from solar noon due to high reflections from surroundings in addition to temporary climate conditions. The corresponding solar radiations are shown in **Fig. 9**. It shows normal profiles of large relative radiation for the two orientations giving large gain as explained above.

On the other hand, a minimum daily average gain of 11.5% was found on 18 April 2014. This low energy gain is due to small declination of about 10^{o} during this month which results in a small difference between the two orientations of collector. The variation of energy gain is shown in **Fig.10** which displays larger gains at 2:30 and 3:00 afternoon due to partly cloudy local condition. The half-hourly variation of solar radiations for that day is shown in **Fig. 11**. Owing to small energy gain, the two radiation profiles are close to each other.

Solar radiations on each of the tilting and horizontal collector as monthly average values are shown in **Fig. 12**. Higher levels were obtained for the month of May. Comparable values were also found for the other months except November and January. However, it is expected that maximum radiation will be at June and July. Radiation levels larger than 700 W/m^2 were observed on the tilting collector. Whereas for the horizontal collector, measured solar radiations were larger than 450 W/m^2. This corresponds to an average sunny climate condition during these months.

For the two months of November and January, lower radiation levels were noticed of smaller than 400 W/m^2 on the tilting collector and smaller than 250 W/m^2 on the horizontal collector. This is due to cloudy and rainy conditions during most of the two months. Furthermore, **Fig. 12** shows that the relative radiation of the two orientations was larger in winter months than that in the other months. This will be explained below. The relative radiation lies in the range of 1.11 to 1.57.

Monthly average energy gains for the months of October to May are plotted in **Fig. 13**. The gain values were found to be approximately within 12% to 60%. For five months, October to February, the gain was larger than 40%. The profile of energy gain is governed by tilt-angle setting, as determined by the solar declination in Eq. (5b), and the local climate condition. Thus, the profile of **Fig. 13** is increasing for October to December as tilting is being larger. Maximum gain value of 57.8% was obtained at December. Then, gain is decreasing as tilting is being smaller. A minimum gain was noticed in May of 12.2%. It is expected that energy gain will further decrease to its minimum value at June and July when tilting is about 11^o. Finally, the data of **Fig. 13** are listed in **Table 1**.

6. CONCLUSION

In this study, a brief updated description of solar collector types and applications were presented. Then, based on field measurements of global solar radiation for tilting and horizontal orientations of collector throughout 8-month period in Baghdad, energy gain and radiation level averages were found, see **Fig. 12**, **Fig. 13** and **Table 1**. On the basis of this study, the following conclusions have been drawn:

1- The tilting mechanism of solar collector is more effective for the winter months as compared to the other months.
2- On the contrary, radiation levels for the solar collector are lower for the winter months than that for the other months.
3- There is a significant energy gain of larger than 40% for October to February with a maximum gain of about 58%.
4- For clear sky condition, the tilting and horizontal orientations of collector are of monthly average solar radiation 910 W/m^2 and 713 W/m^2 respectively.

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NOMENCLATURE

A_a = surface area of concentrator aperture, m^2.

A_r = surface area of collector receiver, m^2.

C = concentration ratio, dimensionless.

CPV= concentrating photovoltaic collector.

CPVT= concentrating photovoltaic thermal collector.

E_i = input energy to collector, kWhr.

E_o = useful output energy, kWhr.

G_{ia} = global solar radiation incident on the aperture, kWhr/m^2.

G_{ir} = incident solar radiation on the receiver, kWhr/m^2.

g = energy gain of collector, dimensionless.

n = nth day of the year, 1$\leq$ n $\leq$ 365.

PV= photovoltaic.

PVT= photovoltaic thermal collector.

r = energy ratio of collector, dimensionless.

S_r = absorbed energy per unit area of the receiver, kWhr/m^2.

t_s = Solar time, hours.

α = lumped parameter for collector optical characteristics: 0 $< \alpha <$1, dimensionless.

β = tilt angle: the angle between the plane of collector surface and the horizontal, 0°≤ β ≤ 90°.

β_o= optimum tilt angle of collector, degrees.

γ = azimuth angle: the deviation of the projection on a horizontal plane of the normal to collector surface from the solar noon, -180°≤ γ ≤180°.

γ_o= optimum azimuth angle of collector, degrees.

γ_s= solar azimuth angle: the angular displacement from south of the projection of beam radiation on the horizontal plane, degrees.

δ = solar declination angle: the angular position of the sun at solar noon with respect to the plane of the equator, -23.45° ≤ δ ≤ 23.45°.

θ_z = zenith angle: the angle between the vertical and the line to the sun, degrees.

ϕ = site latitude: the angular location north or south of the equator, -90° ≤ ϕ ≤ 90°.

ω = hour angle: the angular displacement of the sun east or west of the solar noon due to earth rotation, degrees.

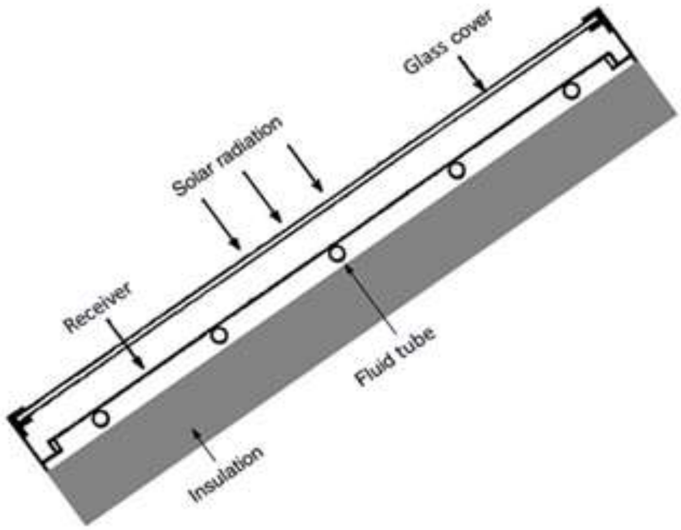
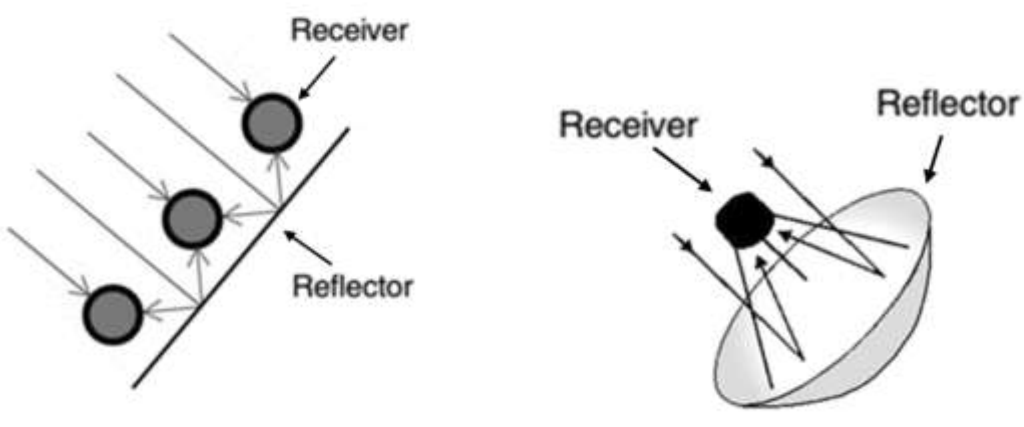


Figure 1. Non-concentrating thermal collector.



(a) (b)

Figure 2. Concentrating thermal collector (a) with linear concentrator (b) with circular concentrator.

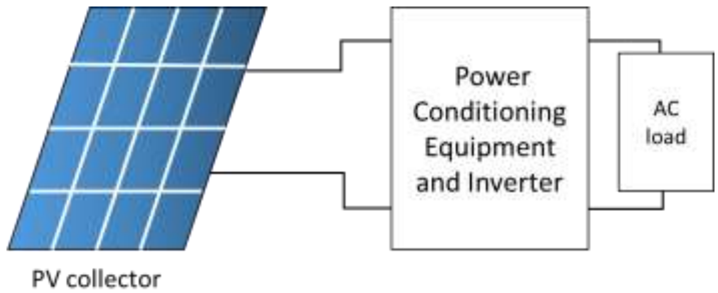


Figure 3. Electric circuit for PV collector.

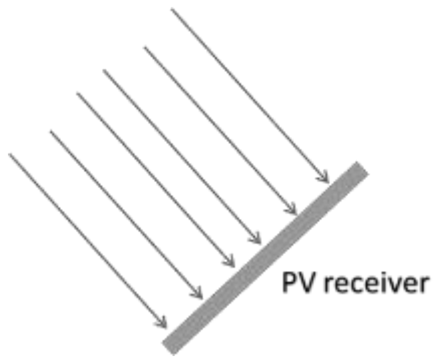
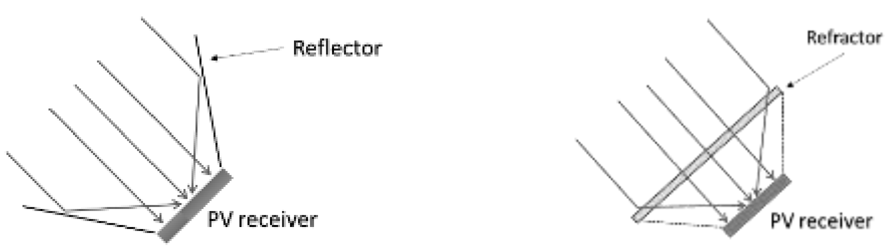


Figure 4. Non-concentrating PV collector.



(a) (b)

Figure 5. CPV collector (a) with reflector (b) with refractor.

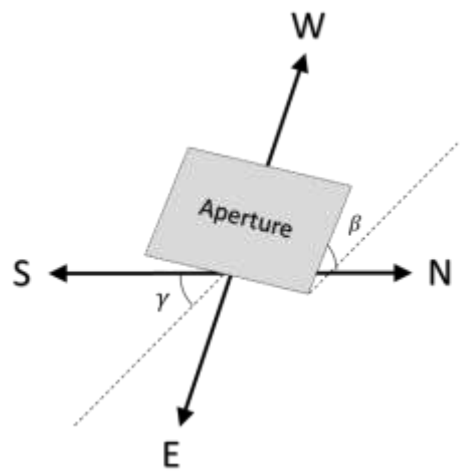
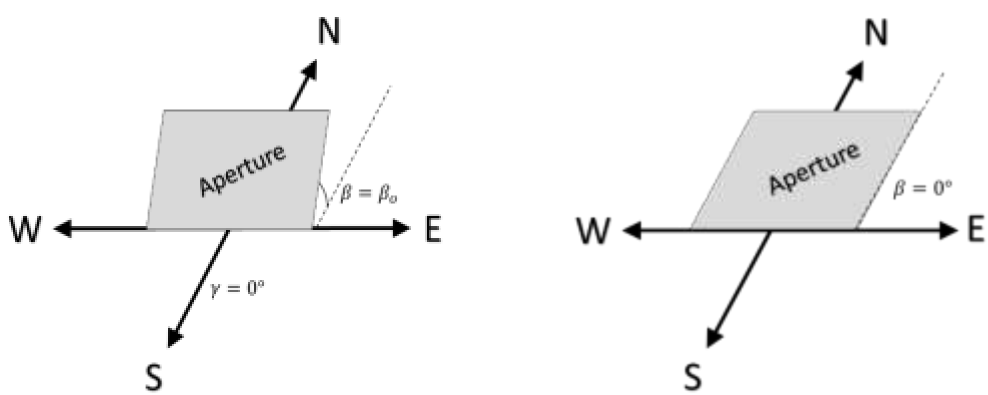


Figure 6. Tilt and the azimuth angles of solar collector.



(a) (b)

Figure 7. Orientations of the solar collector under study: (a) tilting orientation (b) horizontal orientation.

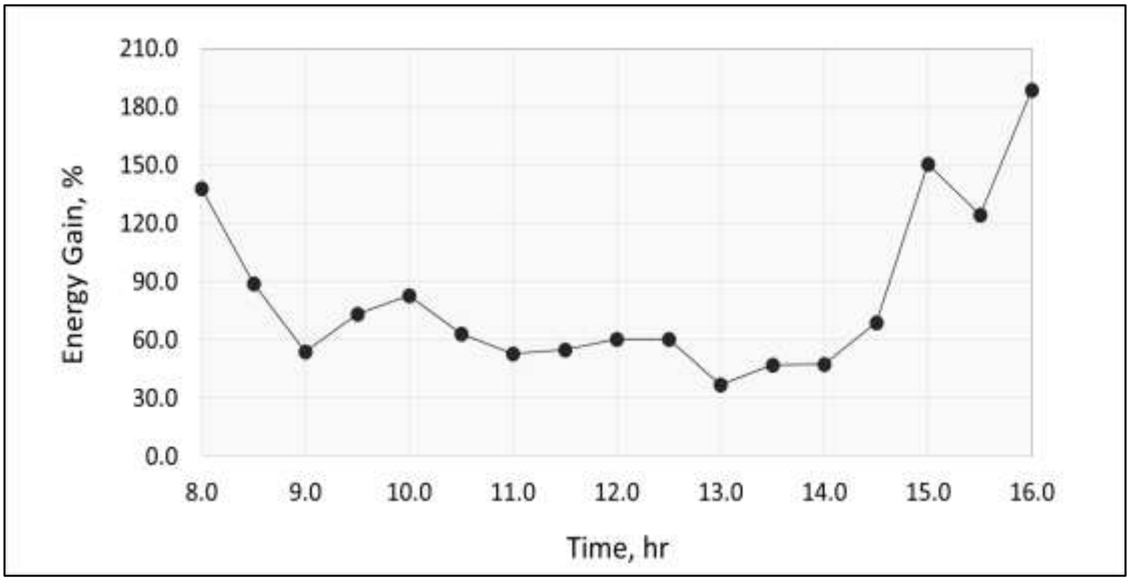


Figure 8. Variation of energy gain on 27 December 2013.

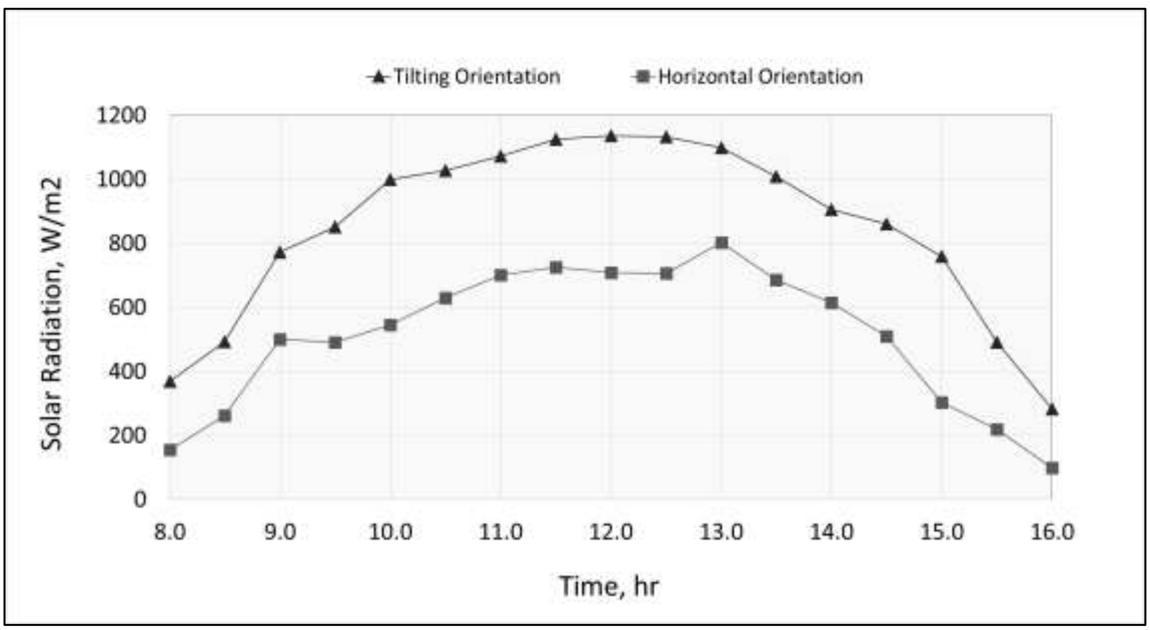


Figure 9. Variation of incident solar radiation on 27 December 2013.

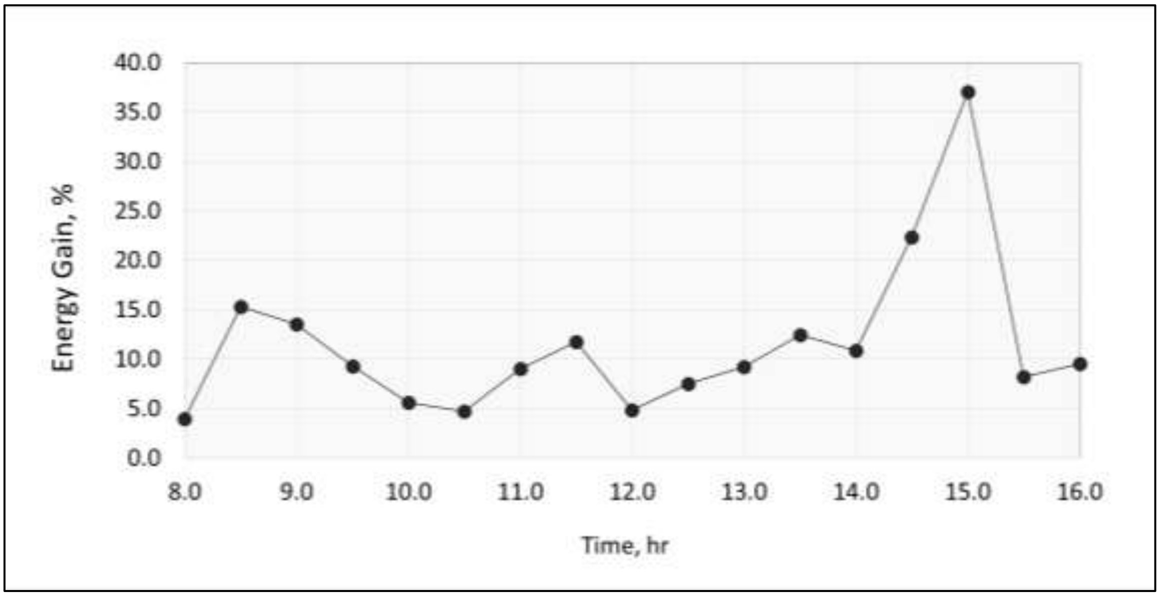


Figure 10. Variation of energy gain on 18 April 2014.

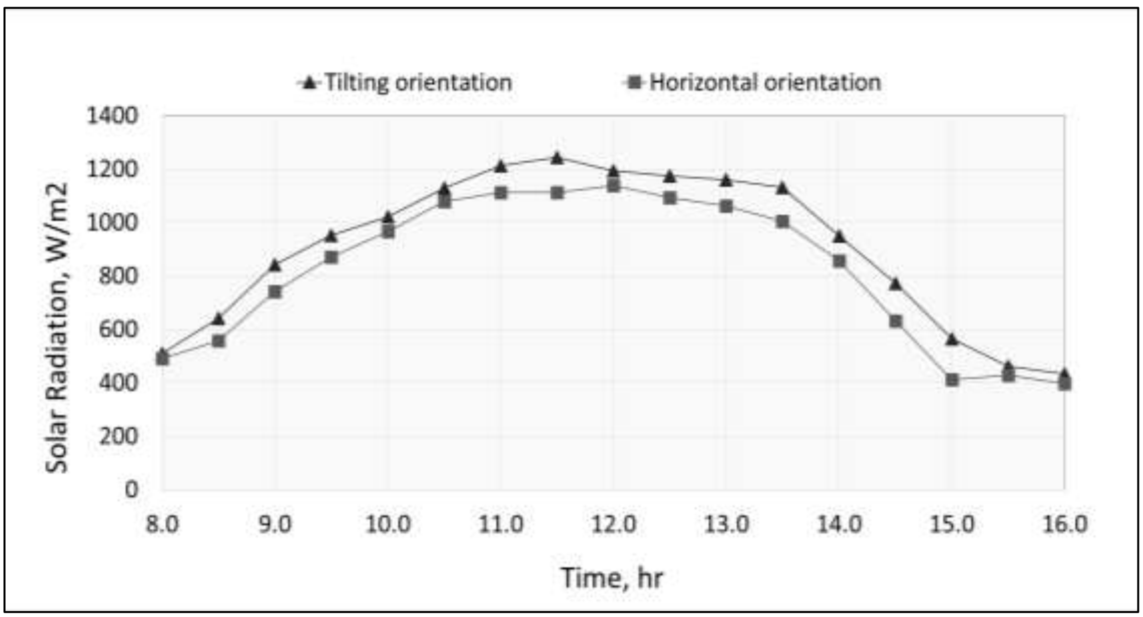


Figure 11. Variation of incident solar radiation on 18 April 2014.

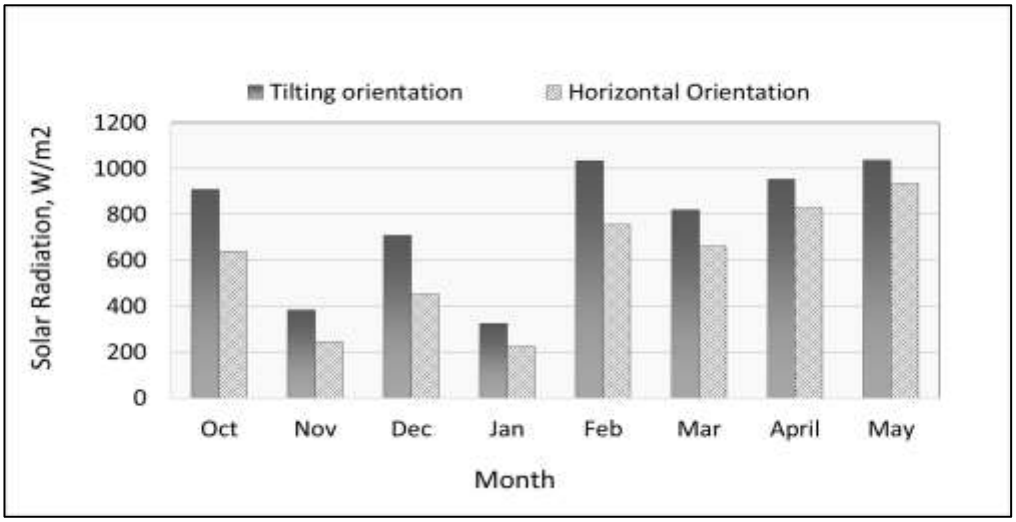


Figure 12. Variation of monthly average solar radiation.

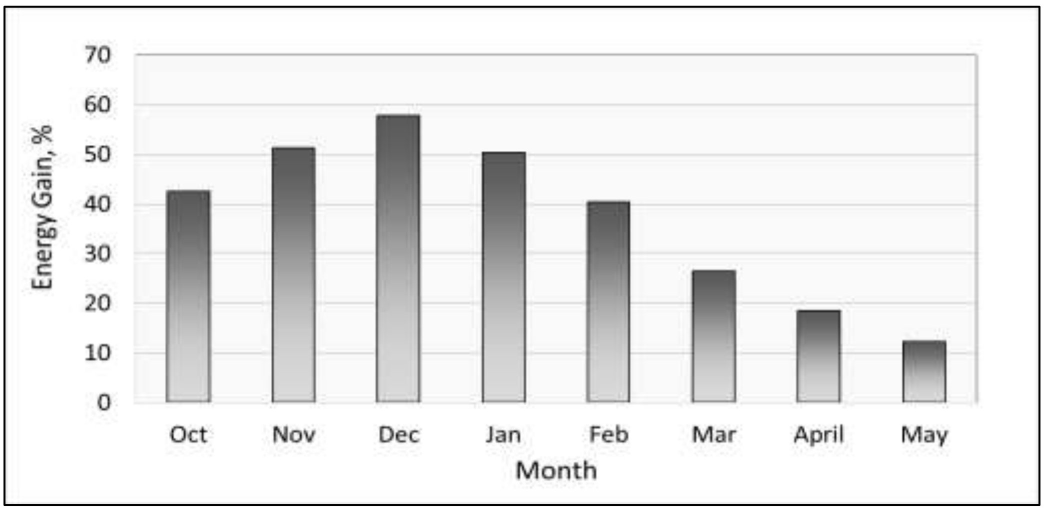


Figure 13. Variation of monthly average energy gain.

Table 1. List of monthly average gain.

Month	Energy Gain, %
October	42.5
November	51.3
December	57.8
January	50.3
February	40.4
March	26.4
April	18.5
May	12.2