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Energy Reports

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Suggested Citation: Awasthi, Anshul et al. (2020) : Review on sun tracking technology in solar PV system, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, pp. 392-405, https://doi.org/10.1016/j.egyr.2020.02.004

This Version is available at:
https://hdl.handle.net/10419/244042

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Energy Reports 6 (2020) 392–405

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Review article

Review on sun tracking technology in solar PV system

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ARTICLE INFO

Article history:
Received 20 July 2019
Received in revised form 29 January 2020
Accepted 6 February 2020
Available online xxxx

Keywords:
Solar energy
Solar PV
Tracking system
Grid
Standalone

ABSTRACT

Solar energy is vast, abundant, cost free, green renewable source of energy. Due to the aforementioned qualities, the world is today researching and exploring the most feasibly optimized way of harnessing this energy and solar tracking system is a result of this quest. This paper begins with a brief introduction to the solar PV cells and the materials used in their construction. It also discusses the types of solar PV systems and types of solar tracking systems. It mainly focuses on the design and performance analysis of the various dual-axis tracking solar systems proposed in recent years. Although the choice on the use of trackers mainly depends upon the physical features of the land but in general this system has proved to be more efficient and advantageous than its single-axis and fixed counterparts.

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https://doi.org/10.1016/j.egyr.2020.02.004
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1. Introduction

Energy is contemplated as an inexorable commodity (Jha and Puppala, 2017). Energy consumption is directly related to the progress of man power, industrialization and economy of the country (Kumar et al., 2017). The increasing demand of energy in progressing civilization is leading to the exploitation of various conventional energy sources. Also the non-renewable energy sources cause the emission of green house gases and other environmental damages. India accounts for 7% of the total global emission which is much lower than those of the US which makes up to 15% of total global emission (Theconomictimes, 2019).

In order to limit and reduce the environmental degradation, the encouragement of the development of green technologies and their adoption is necessary (Paulo and Porto, 2018). Solar, wind, biomass, hydro and all the various renewable sources of energy which do not cause any environmental pollution during their usage must be adopted and replace all the conventional sources of energy.

Among all these, solar is one of the most abundant sources of energy. About $1.2*10^5$ TW of solar radiation reaches the earth's surface (Li et al., 2018). Solar radiation is having the greatest potential for green technologies since it is very abundant, clean, cost free and inexhaustible source of energy (Paulo and Porto, 2018).

In India, the capacity of solar energy has increased 8 times in 4 years, statistically 2.63 GW to 22 GW from 2014 to 2018. India is going to reach a mark of 227 GW of non-conventional energy. However solar energy can be utilized during day time only (Theconomictimes, 2019).

From the past many years, fixed or static solar systems were in use but now with the advancement of technologies the efficiency of solar systems is being increased by using single axis and dual axis solar tracking systems which can track the position of the sun according to the season and time of the day. Though fixed racking can accommodate harsher environmental conditions easily and tracking being a more complex system requires more site preparations, additional trenching for wiring and some additional grading (Solar Power World, 2016), tracking systems are being used widely as they have improved the efficiency of energy extraction and in a way, has optimized the process. Neville (1978) through his paper showed that the dual axis tracking system manages to give maximum amount of output energy where single axis tracking system's energy output falls by 5%–10% and fixed system's fall by 50%. Arlikar et al. (2015) showed that a 3D solar tracker based solar panel receives more energy than a fixed one. Many theoretical and experimental papers have been published on this subject in the past. Relationship for slope and azimuth expressions between single axis and dual axis tracking systems is given by Braun and Mitchell (1983). Though tracking has improved the output in many cases but it does not guarantee better output. Sharaf Eldin et al. (2016) showed that tracking the sun is not that feasible in hot regions. They used mathematical model is validated experimentally and then applied for several environments, i.e. hot as well as cold regions. They found that the gain in electrical energy from tracking the sun is about 39% in case of a cold city as Berlin, Germany. While the gain in energy does not exceed 8% in case of a hot city as Aswan, Egypt, due to overheating of the PV panels. However, if the energy needed for running the tracking system, which ranges from 5% to 10% of the energy generated, is included in this analysis then tracking the sun will not be feasible in hot countries.

There are many wide applications of solar energy as energy resource and one such is Multiple-effect distillation. The impact of using tracking systems in MED plants is depicted by Gholinejad et al. (2016). In his study he concluded that the solar MED plant using full tracking system, N–S tracking system, E–W tracking system and polar axis tracking system produced 341%, 135%, 246% and 291% more fresh water respectively in comparison to that of a fixed system. There are many such different applications deploying tracking systems in the solar plants in order to increase the output and efficiency of the overall system.

This paper presents a comprehensive review on performance analysis of dual axis solar tracking systems. It begins with a brief introduction about solar cell, electricity generation using PV cells. A preview on the types of solar PV systems and the types of solar tracking systems which were introduced for increasing the performance of the solar PV systems and for making the maximum usage possible out of the available solar energy, is also presented in this paper. Furthermore a detailed analysis of dual axis solar trackers on the basis of different designs, mechanisms used and their performances is shown. In addition to this the current challenges in the application of these solar systems are discussed.

1.1. Electrical generation from solar cells

For converting the solar energy into electrical energy an electrical device, photovoltaic cell or solar cell is used. Silicon like semiconductors constitute the solar cells and large number of solar cells combine to form a PV solar panel.

To facilitate a positive charge, one layer of the cell is usually doped with Boron or any trivalent impurity (p-type semiconductor) and to facilitate a negative charge, other layer is doped with Phosphorous or any pentavalent impurity(n-type semiconductor). And when these two different kinds of semi conductors are brought together they form a junction said to be PN junction. Gradients of electron and hole concentration formed near the surface cause holes to diffuse from p-type to n-type and electrons to diffuse from n-type to p-type (Fan et al., 2018).

When photons from the sunlight strikes the solar cells, then due to the collision, some energy of the photons is transferred to the silicon electrons and this energy is large enough to make the electrons free from the parent silicon atom. The free electrons move and get collected within the n-type silicon. The electrodes are linked to the external circuit and the flow of electrons from n-type to p-type through electrodes and the external circuit generates the electric current (cosmosmagazine, 2017).

Several types of solar panel materials which are used in constructing these panels are mentioned in Table 1 (matmatch, 2018; Wikipedia, 2019; energy.gov, 2019; Wikipedia, 2019b).

1.2. Types of PV systems

Solar PV and Storage Systems are classified Into Three Types-

- Grid tied or grid Direct PV System
- Off Grid PV System
- Grid/Hybrid or Grid — Interaction System with Energy Storage

Table 1
Different types of materials used.

S. No.	Category	Solar panel types	Efficiency & power output	Characteristics	Applications
1.	1st generation solar panels.	♦ Mono-crystalline Solar Panels. ♦ Polycrystalline Solar Panels.	• ∼20% • High power output. • ∼15%. • Power output is same as mono-crystalline solar panels.	• Purest one. • Occupy less space. • It lasts for longer time. • Optimized for commercial use. • Shorter life span as it is affected by heat & high temperature. • This type of solar panels have squares, its angles are not cut & it has a blue, speckled look.	• They are most commonly used in conventional surroundings.
2.	2nd generation solar panels.	♦ Thin film solar cells. ♦ Amorphous silicon solar cells.	• Module efficiency → 16%–17%. 9%	• Less expensive. • Easiest to produce. • Flexible. • Carry shorter warranties because their lifespan is shorter than mono & polycrystalline. • Take a lot of space for installation. • Uses a triple layered technology. • Low in cost.	• They are mainly used for photovoltaic power stations, integrated in buildings on smaller power systems.
3.	3rd generation solar panels.	♦ Biohybrid solar cell.	• The conversion from chemical to electrical energy becomes much more effective [up to 1000 times more effective than 1st generation types of solar panels].	• Generates electricity using organic material.	
		♦ Cadmium Telluride (CdTe) Solar Cell. ♦ Concentrated PV cell.	• The record efficiency for CdTe solar cell is 22.1% by first solar, while first solar recently reported it commercial module efficiency to be 16.1% at the end of 2015. • Efficiency rate is up to 41%.	• Enables the production of solar cells at relatively low cost & thus a shorter payback time. • Require least amount of water for production. • Only disadvantage of using CdTe is that it is toxic, ingested or inhaled. • Multifunction type of solar panel. • Have high temperature & efficiency rate. • Most efficient type of solar panel. • Sometimes cooling systems are used to bundle the sun rays & thus it improves the efficiency of solar panels.	• HCPV (high concentrated photovoltaic) are best suited for areas with high direct normal irradiance.

1.2.1. Grid tied or grid-direct PV system

This is a basic solar setup having a standard grid-tied inverter. The grid-tied solar PV system does not have battery bank for storage. From grid-tied system power can be generated and utilized during the day time only. This system is very cost effective, simple to design, easily manageable and requires less maintenance. A schematic representation of the system is shown in Fig. 1. Lowering the energy bill is the main object of the grid-tied system (Solarpowerworldonline, 2015).

The solar panels mostly produce more electricity than required by the loads. Hence this excess electricity can be given back to the grid instead of storing it in the batteries. And some extra revenue can be generated by selling this excess generated power by the solar panel, which will further result in reducing the LCOE (levelized cost of energy of system) (Ghenai et al., 2018). As the power generated by the PV panels is in DC so an inverter is needed to convert the DC into AC.

The disadvantage of grid-direct system is that it can be used only during the day time. Power cannot be stored for any future uses like at times of power outages. However this disadvantage can be overcome by using a battery bank to store the generated power during the day time but this new setup will eventually increase the cost of the system (Solarpowerworldonline, 2015).

1.2.2. Standalone/off grid solar PV system

This system is beneficial for the customers who cannot connect their load easily to the grid (Solarpowerworldonline, 2015). Batteries are used in off-grid solar PV systems for the storage of the generated electricity during day time which can be used in future or during any emergency case (like a cloudy day) and during night (Ghenai et al., 2018). Year round conditions and weather changes have to be considered while designing this system. In case if sun does not appear for some continuous days or if snow gets accumulated over the PV panels, then back-up generators are needed (Solarpowerworldonline, 2015). Gasoline, diesel, petroleum, propane can be used to run the generator. The AC output of backup generators can be put directly into use or for storing in batteries it can be converted into D.C. A schematic representation of the system is shown in Fig. 2. The advantage of this system is that it gives sufficient energy to a household and it can power the places which are far away from the grid. Off grid systems have more components and these systems are comparatively costlier and expensive than grid-direct systems (Ghenai et al., 2018).

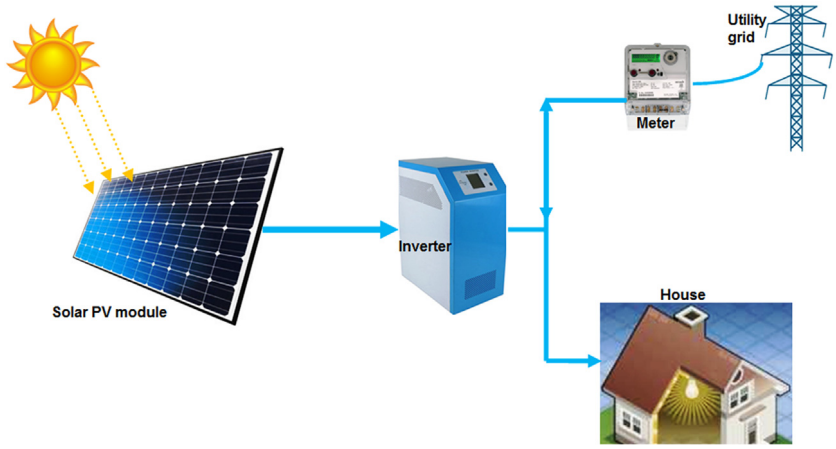


Fig. 1. Grid tied/direct PV system.

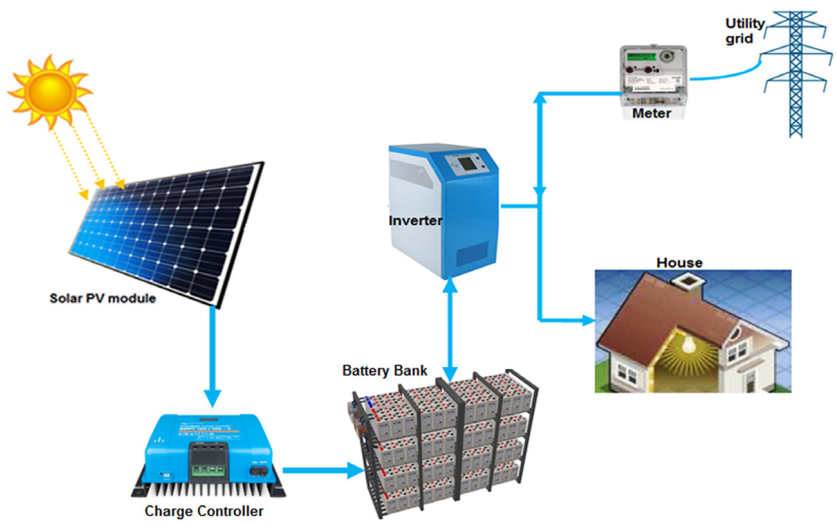


Fig. 2. Standalone/off grid PV system.

1.2.3. Grid/hybrid or grid interactive system

This system is ideal for the customers who are already connected to the grid system and want a battery backup. This system gives the advantages of both grid-direct and off grid system. This system can help in lowering the utility bills through widespread incentives. However this grid system is not used for some widespread incentive programs only, if there happens to be any power outage then the energy from the battery bank during such emergency can be utilized (Solarpowerworldonline, 2015). During peak demands also the stored energy in the batteries can be utilized (Sultan et al., 2018; energyinformative, 2012). The Performance analysis of some Solar PV systems is given in Table 2.

2. Classification of solar trackers

Solar tracking systems have many bases of classification. It can be classified on the basis of the control system used, drivers used, tracking strategy used or on the basis of degree of freedom of the movement exhibited by the system.

2.1. On the basis of control system used

2.1.1. Closed loop tracking system

Irrespective of the driving system used for the movement of the tracker, be it some passive system or some pre-defined algorithm on the basis of mathematical calculations based on sun's trajectory, when sensors are deployed to detect the position of the sun which is then feed-backed to the system so that the comparator/ microprocessor used in the system can detect the error and give the required actuating signal to the motors to correct the error, then the system is said to be working on the principles of feedback control system. And the trackers deploying the above mention system are known as closed loop sun trackers. A dual axis tracking system proposed by Stamatescu et al. (2014) consists of 4 PV cells as sensors, 2 motors and a tri-positional control mechanism. The radiation is measured by sensors and the motors are controlled accordingly.

2.1.2. Open loop tracking system

This type of system uses a controller which gives the driving signal to the motor purely on the basis of current data inputs and operating algorithm of the system alone. It has no feature of observing and evaluating the output data in regards to the desired output. Thus it is cheaper and simpler to implement in comparison with the closed loop tracking system but it involves no rectification process and thus the algorithm alone has to ensure that it achieves the desired goal. Al-Naima and Yaghbian (1990) constructed a dual axis microprocessor based sun tracker which used a tracking strategy purely based on the calculations of the astronomical coordinates of the sun. It showed better tracking capability than the conventional sensor controlled counterparts.

Table 2
Performance analysis of some Solar PV systems.

S. No.	Author's name	System implemented	System performance	Reference
1.	Ghenai & Bettayeb	• A grid connected renewable energy system to meet the electric load of the building with high penetration of renewable energy, low greenhouse gas emissions & low cost of energy.	• With a solar PV capacity of 500 kW & fuel cell hybrid capacity of 100 kW integrated with grid, the total energy generated from grid-tied renewable energy system to meet the desired load is 26% from the grid, 42% from the solar PV & 32% from the fuel cell.	Ghenai and Bettayeb (2019)
2.	Satsangi et al.	• For the year 2016, the performance of a 40 kW rooftop grid interactive solar photovoltaic plant was evaluated, following IEC standard 61724.	• System efficiency was 8.51%, annual average PV array efficiency was 4.36% & inverter efficiency was 90.9%.	Pritam Satsangi et al. (2018)
3.	Numbi & Malinga	• Under the feed-in-tariff (FIT), an optimal model of a 3 kW residential grid interactive solar PV system is implemented.	• Simulation output showed energy cost saving of 69.41% when the energy cost management is used for the residential grid interactive PV system.	Numbi and Malinga (2017)
4.	Abdul Ghafoor & Anjum Munir	• Study about an off-grid (stand alone) photovoltaic system for electrification of a single residential household in Pakistan.	• The peak power for this system was calculated to be 1928 Wp.	Ghafoor and Munir (2015)
5.	Al-addous et al.	• Off-grid PV system with a total nominal power of 10.4 kWp was installed in Jordan Valley & the environmental impact was observed on PV systems performance	• The efficiency of PV module is greatly affected by temperature rise.	Al-Addous et al. (2017)
6.	Ali et. al	• The variable step-size MPPT algorithm is proposed & used for three phase grid-tied PV system.	• The algorithm improves the system output & reduces the steady state voltage oscillations, which results in improvement of system efficiency. Also, the proposed MPPT algorithm improves the system tracking efficiency from 92.6% to 95.4%.	Ali et al. (2018)

2.2. On the basis of driving system used

2.2.1. Passive solar tracking system

This system does not involve mechanical drives to orient the panel towards the sun's radiations. Instead it uses some low boiling point compressed gas fluid or shape memory alloys as actuators which on receiving unbalanced illumination, forces the panel to undergo some angular movement so as to re-establish equilibrium of irradiance by inducing thermal expansion in expansible gases or in on-shape memory alloys. When one side of the liquid gas receives more amount of heat energy than the other, then the gas expands and moves towards the other side of the tracker. It causes an unbalanced gravitational pull and forces the panel to tilt until a point of equal illumination is reached (Parmar et al., 2015). Though it is less complex and effective but it fails to give high efficiency at low temperatures. Poulek (1994) developed a new low cost shape memory alloy based sun tracker which could collect up to 40% surplus energy in comparison to the fixed tilt collectors.

2.2.2. Active solar tracking systems

These systems use electrical drives and mechanical gear trains to orient the panels normal to the sun's radiations. It uses sensors, motors and microprocessors for the tracking and are more accurate and efficient than the passive solar trackers. But on the other hand they are needed to be powered and consume energy. When the trackers are not in proper alignment with the sun, the sensors receive different illumination and create a differential signal which is then used by a comparator or a microprocessor to determine the appropriate movement in the appropriate direction. The required signal is then given to the motors to work accordingly. This process stops at a point where the sensors receive equal illumination and the PV module is normally aligned with the sun's radiations. An active sun tracker was used by Abdelghani-Idrissi et al. (2018) while experimenting for thermal efficiency enhancement. They found that the tracker based system showed an overall gain of 40% in stored thermal energy in comparison to the fixed one.

2.3. Based on degree of freedom

Degree of freedom represents the number of directions in which independent movement can occur. Based on this, tracking systems have been classified into single axis and double axis solar tracking systems. But before driving into this classification, let us have a look on different types of axes and angles which play an important role in these tracking systems. To determine appropriate locations and directions, these parameters play an imperative role.

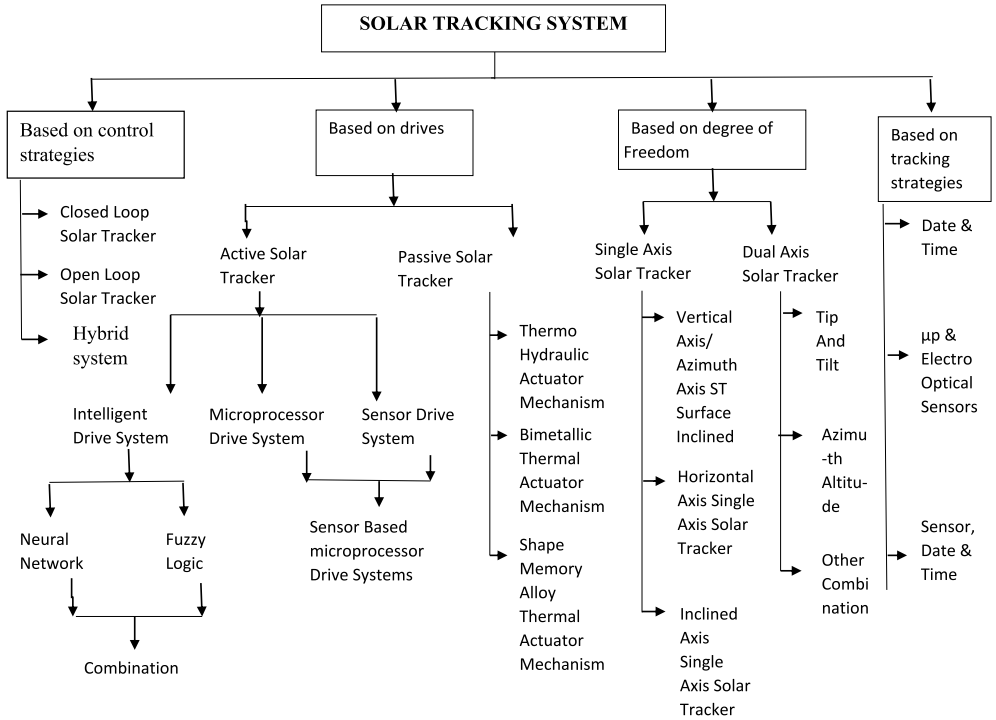
Latitude: It is a measure of the position of a point on the earth's surface determining how north or how south the point lies with respect to the equator. It is measured in angles ranging from 0° at equator to 90° at the poles, as illustrated in Fig. 3.

Angle of incident: The angle between the incident ray of the sun and the line normal to the plane is known as angle of incidence, as indicated in Fig. 4.

Declination angle: It is the angle by which the earth's equator is tilted with respect to the earth's orbit around the sun, as indicated by 'δ' in Fig. 5.

Elevation/ altitude angle: It is the angle between the horizon and the line joining the center of the sun to that of the earth (α), as illustrated in Fig. 6.

Zenith angle: It is the angle between vertical axis and the line joining the center of the sun to that of the earth (z), clearly, $z = 90° - \alpha$ as illustrated in Fig. 6.



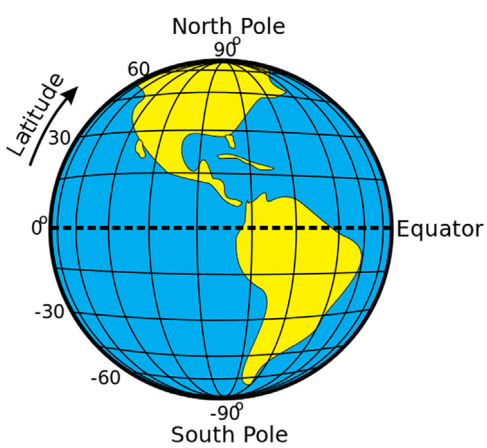


Fig. 3. Latitude (geolounge, 2014).

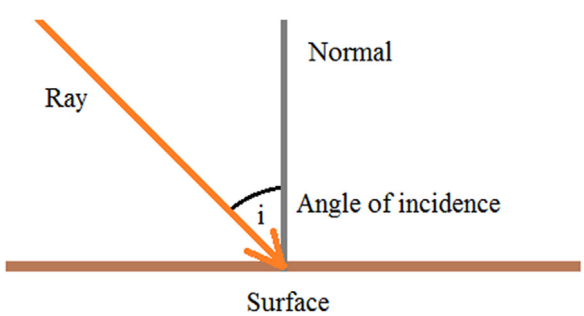


Fig. 4. Angle of incidence.

Tilt Angle: It is the angle between the PV solar panel and the horizontal axis, as illustrated in Fig. 7. Angle of incidence is a form of tilt angle (Hafez, 2017).

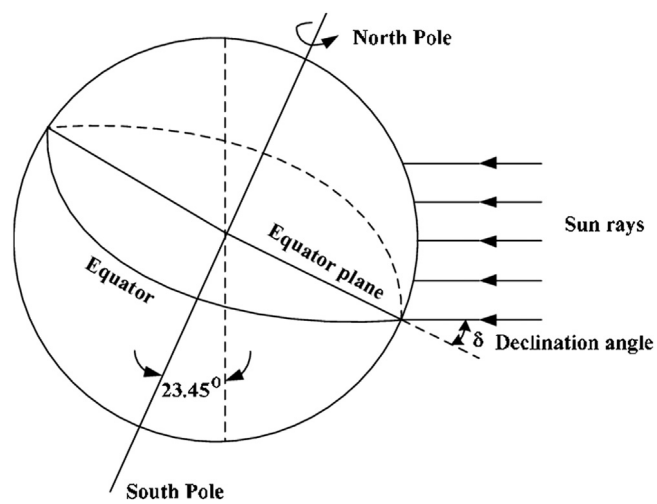


Fig. 5. Angle of declination (Karafil et al., 2015).

Solar Azimuth Angle: It is a type of an angular measurement in the spherical coordinate system. The vector from an observer to the point of interest is projected perpendicularly on the reference plane and the angle between this projected vector and the reference vector is known as Azimuth (Wikipedia, 2019a).

In case of solar azimuth angle, the point of observation is the center of earth and point of interest is the center of sun. Traditionally the reference vector is taken due south, but the most commonly accepted convention is to take the reference vector due north as illustrated in Fig. 8. The angle is measured clockwise i.e. East-90°, South-180°, West-270° [definition used by NREL].

2.3.1. Single axis solar tracking system

This system involves a single axis about which the rotation is possible in order to align the panel perpendicular to the sun's

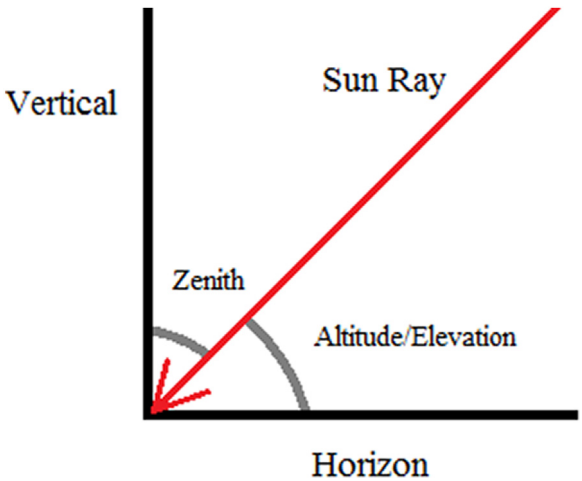


Fig. 6. Zenith and altitude angles.

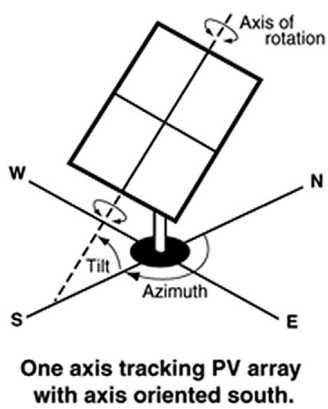


Fig. 7. Tilt angle (pveducation, 2019).

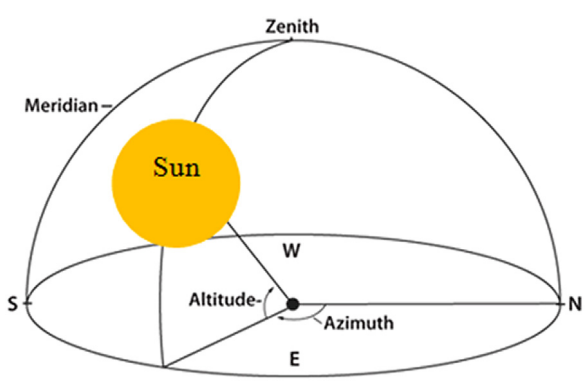


Fig. 8. Azimuth and altitude angle (Sidek et al., 2014).

radiations. The most preferable orientation is said to be alongside the north meridian axis (Mousazadeh et al., 2009). Batayneh et al. (2019) proposed a discrete single axis solar tracker that actuates only thrice in a day based on the optimal angle calculations. Experimental results showed that this tracking system yielded about 90%–94% of solar energy which is produced by a similar continuous solar tracking system.

There are several configurations of single axis tracking systems which includes vertical aligned (VSAT), horizontal (HSAT), horizontal with tilted modules (HTSAT), tilted (TSAT) and polar aligned (PSAT). SATs are cheaper and less complex but less efficient in comparison with DATs.

2.3.2. Double Axis Solar Tracking System (DATs)

It involves two axes of rotation which are usually perpendicular to each other. It requires a more complex control system and is more efficient than single axis tracking systems (SATs). Experiments carried out on a 300 kW double axis parabolic trough collector by Sun et al. (2016) showed that the optimized double axis tracking strategy proposed by him managed to boost efficiency by 15%–17% in comparison to that of single axis tracking strategy.

2.4. Based on tracking strategies

2.4.1. Date and time

This tracking system solely uses predefined algorithms based on mathematical calculations about sun's trajectory to determine the sun's position at a particular time in order to orient the PV panels accordingly. No feedback loop or any sensor is involved. Hence, the algorithm is solely responsible for the efficient working of the system. Nuwayhid et al. (2001) developed a simple and low cost tracking parabolic concentrator whose functioning was totally based on the pre calculated azimuth and altitude angles. It was successful in generating temperatures in the range 200–600 °C whereas its fixed counterparts manage to achieve between 80–200 °C.

2.4.2. Microprocessors and electro optical sensors

It involves sensors for the detection of the sun's position. And the signal is fed to the microprocessor which further instructs (gives signal) to the motors to the needful. Kalogirou (1996) designed sufficiently accurate single axis solar tracking system using 3 light dependent resistors as sensors, an electronic circuit and a dc motor with reduction gears. Here sensors give the input to the electronic circuit which further actuates the motor.

2.4.3. Sensors, date and time

Basically it works on a predefined algorithm but to have a check on the whole operation sensors are involved. They verify the position of the sun and drives orient the panels accordingly. Rubio et al. (2007) presented a double axis hybrid solar tracking system. The name hybrid here points to the mixed tracking strategy used, open loop tracking which is based on solar movement model and closed loop tracking which feeds back a signal proportional to the generated output power measured by sensors.

3. Dual-axis solar tracking system

Many studies in the past have shown that in spite of having complex mechanism, higher cost and need of maintenance, dual axis solar tracking is still preferred due to higher efficiency and its performance. Moreover which tracking system should be deployed depends upon many parameters and the physical features of the land. Some parameters which are used in determining the efficiency of a dual-axis solar tracking system are listed in Table 3.

Roth et al. (2004) constructed a closed loop dual axis solar tracking system with four quadrant photo detectors and 2 small DC servo motors. It also allowed automatic measurement of direct solar radiation using a pyrheliometer. Photo detectors were used to detect the position of the sun and direct the 2 DC motors to move such that the sun's image remains in center of the four-quadrant photo detectors. Under cloudy condition, a computing program would take over and guide the motors until the sensors

could start sensing the sun again. They concluded that the radiation falls nearly to zero for solar irradiation below 140 W/m^2 but above this value, the system works fine.

As the temperature of the PV cell increases, the efficiency of the system goes down with a drop of 0.5% per degree rise in temperature (Moharram et al., 2013). Thus to maintain a satisfactory level of efficiency, the temperature should also be in control and many have suggested different models keeping this problem in mind. And one such model was presented by Rahimi et al. (2015). Their paper introduces the design and applications of a hybrid sun–wind tracking system employing cooling effects of wind with advantage of dual axis solar tracking which enhances the power output appreciably. The comparison is done between dual axis sun tracking system, hybrid sun–wind tracking PV system and a stationary PV system. This system tracks the sun along two axes using two actuating motors and wind with one axis using a single motor. In comparison with the fixed PV panel, the solar tracking panel produces 39.43% more energy on a daily basis whereas the hybrid tracking system produces 49.83% more energy than that of the fixed one.

Solar energy has many wide applications and one of those is solar cooking which have been mainly witnessed in the developing countries. This is also constantly demanding an improvement in efficiency regarding which many studies have been done in the past and one such initiative was taken by Al-Soud et al. (2010). They designed, built and operated a parabolic solar cooker with automatic two axes sun tracking system using a programmable logic controller (PLC). Its execution of the program is based on pre-calculated solar (azimuth and elevation) angles and speed of the motors. It was a cost effective and less maintenance demanding model. It demonstrated its ability to heat up the water to about 90 °C where the maximum ambient temperature was registered to be 36 °C. It also allowed the food to be left in, all day long without burning.

Many different works have been done by many researchers in this field. A unique system of solar tracking using image processing was built by Abdollahpour et al. (2018). Its working principle is based on the relationship between an opaque object and its shadow i.e., larger the angle between the object and the surface on which the shadow is casted, longer will be the shadow and when the surface is perpendicular to the sun rays i.e., the sunshine angle is 90° then no shadow is casted on the surface. By measuring the ratio of the shadow of the object to its height and the angle of the shadow casted on the surface with respect to north, the position of the object with respect to the light source can be determined. This data is then fed to the microcontroller which actuates the motors such that the surface (PV panel) becomes perpendicular to the sun rays and no shadow is casted upon the surface. For this purpose, a shadow casting object, a webcam, electronic circuits, computer controller and stepper motors were deployed. This tracking system was successful in following the sun with an accuracy of ±2°.

To increase power output and power reliability, hybrid systems utilizing both solar and wind resources simultaneously can be adopted (Bernal-Agustı´n and Dufo-Lo´pez, 2009) but the system has to be economical and its efficiency would be depending on many parameters. Many studies have been going on to make it a success and one such attempt was made by Sinha and Chandel (2016). To identify the optimal combination of fixed/sun tracking PV systems in order to enhance the power generation potential of the existing roof mounted PV-micro wind hybrid systems, they conducted a study in which 6 different types of tracking PV systems and their performances were compared with that of the fixed tilt system. Tracking systems used in this study were: Horizontal axis monthly adjustment (HAMA), Horizontal axis weekly adjustment (HAWA), Horizontal axis daily adjustment (HADA), Horizontal axis continuous adjustment (HACA), Vertical axis continuous adjustment (VACA) and two axis tracking system. Despite of higher cost, the two axis system was found to be more advantageous than the other systems.

Solar Concentrator technology has also become more prevalent today and many are working to create a more efficient and feasible SPC model. Skouri et al. (2016) designed, realized and compared three pilot sun tracking systems which were able to follow the sun's position along both the axes (azimuth and elevation angles). LDR based sun tracking system was the cheapest of all but was less accurate in cloudy days whereas date and time based sun tracker using screw nut actuators being independent of climatic conditions exhibited more accuracy but had less movement stability accounting to screw nut actuators. But the date and time based sun tracker using reduction gear units had an advanced accuracy with a tracking error inferior to 0.2° with good movement stability, low maintenance and ease of installation.

Flores-Hernandez et al. (2017) proposed a study of dual axis sun tracker using a mechatronics design and photovoltaic system driven by a robotic sensor. Sun tracking system generally consists of mechanical devices that adjusts PV modules towards the sun, compensating for changes in both the altitude angle of the Sun [during the day] and the latitudinal offset of the sun [during seasonal changes] and changes in the azimuth angle (Clifford and Eastwood, 2004). Trajectory tracking controller is used to drive these types of systems. The design methodology was based on mechatronics concepts, particularly the VDI 2206 standard, which is the guide for proper development of the mechatronic system, including verification and validation. This technique provides an efficient energy collection system. Experimentally it is illustrated that it achieves better performance than fixed as well as single axis tracking mechanisms.

Away and Ikhsan (2016) projected a dual axis solar tracker with three light dependent resistors which are identical, in tetrahedron shape and is able to track the sun or the place where the intensity of visible light is maximum. When this design is compared with previous type of solar tracking sensors, it showed wide field of view, accuracy and effectiveness.

Abdallah and Nijmeh (2004) proposed a two axes solar tracker with programmable logic controller which is used to control the motion of the solar tracking surface. This method works efficiently in all weather conditions. It is found that with the use of two axes tracking surface, there is an increment in total daily collection of about 41.34% as compared to that of 32 degree tilted fixed surface.

Seme et al. (2017) proposed the design of a two axis solar tracking system together with an open loop control system of electric drive which yields good results in terms of tracking the trajectory of the sun. It is found that with the proper selection of the elements of an electric circuit and photo sensors being used for the system control, the tracking of the system is very precise. It was evaluated that the dual axis solar PV tracking system produced 27% more electrical energy than the fixed systems.

Khalifa and Al-mutawalli (1998) performed a study to show the effect of using sun tracking system on the thermal performance of compound parabolic concentrator [CPC]. For the purpose of study and investigation, the electromechanical two axis tracker and two identical CPC collectors were designed. By performing two experiments, in the first, a batch feeding was used where no flow through the collector was allowed. In the second, different flow rate of steady water were used for experimental purpose. In both the experiments, the variation of temperature were monitored according to which it showed that the tracking CPC collector showed a better performance result with an increase in the collector energy of 75% when it is compared with an identical fixed collector.

Chen et al. (2015) proposed a field programmable gate array [FPGA] based intelligent sun tracking system. It uses an NI9642

Table 3
Parameters used in determining the efficiency of a dual-axis solar tracker.

S. No.	Parameter	Formula	Remarks	Nomenclature	Reference
1.	Solar radiation ratio	$R_b = \frac{H_b}{H} = \frac{\cos\theta}{\cos\theta_z}$	It is defined as the ratio of direct solar radiation and instantaneous solar radiation.	H_b = Direct solar radiation (W m^{-2}) R_b = Solar radiation ratio H = Instantaneous solar radiation (W m^{-2})	Ahmad et al. (2013b)
2.	Diffuse solar radiation	$H_d = Hk_y$	It is defined as the diffuse solar radiation received by the PV's sensing surface.	H_d = Diffuse solar radiation (W m^{-2}) K_y = Clearness/cloudiness index	Yilmaz et al. (2015)
3.	Declination angle	$\delta = 23.45 \sin\left[2\pi\left(\frac{n+284}{365}\right)\right]$	It gives declination angle for any nth day of the year (Cooper's equation)	δ = Declination angle (rad) n = nth day of the year	Stanciu and Stanciu (2014)
4.	Solar azimuth angle	$\gamma_s = \cos^{-1}\left[\frac{(\sin\alpha_s \sin\Psi) - \sin\delta}{\cos\alpha_s \cos\Psi}\right]$	Surface zenith angle (γ) is 0° for south oriented surfaces but $\gamma = \pi - \gamma_s$ for other solar tracking systems.	γ_s = Solar azimuth angle (rad) α_s = Solar elevation angle (rad) Ψ = local latitude	Ahmad et al. (2013a)
5.	Maximum solar radiation	$H_n = \frac{H}{\cos\theta_z}$	It shows the relation between maximum solar radiation and incident solar radiation.	H_n = Maximum solar radiation (W m^{-2}) θ_z = Zenith angle (rad)	Ahmad et al. (2013b)
6.	Clearness index or Cloudiness index	$K_y = \frac{H}{H_n}$	It is the ratio of instantaneous solar radiation and maximum solar radiation and gives idea about the amount of clouds in the area.		Yilmaz et al. (2015)
7.	Inclination/zenith angle	$\beta = \left[\frac{\pi}{2} - \alpha_s\right]$	It is calculated using the data of elevation (α_s).		Zhong et al. (2011)
8.	Direct solar radiation	$H_f = H_n \cos\theta = HR_f$	PV receives the maximum solar radiation when the incidence angle is 0°.		Ahmad et al. (2013b)
9.	Clock angle or Hour angle	$\omega = \left(\frac{Minutes\ before\ noon}{4}\right)$	The minutes are considered positive for afternoon and negative for before noon.	ω = clock angle (min)	Yilmaz et al. (2015)
10.	Total amount of solar radiation	$H_T = H_{gr} + H_s + H_{dp}$	This gives the total amount of radiation reaching the surface of the PV panel.	H_{dp} = Diffuse solar radiation (W m^{-2}) H_{gr} = Reflected radiation (W m^{-2}) H_T = Total solar radiation (W m^{-2})	Cruz-Peragón et al. (2011), Talebizadeh et al. (2011)

controller to integrate the dual axis solar tracking system with Maximum Power Point Tracking [MPPT] in order to increase the output power of the solar panels. They are indulged with many expert and intelligent functions so that they can start automatically during the daytime and return back to their initial position during the night time. This system is assisted with MATLAB so that the system can be switched to dual axis sun tracking, single axis sun tracking and fixed solar panel according to the need of the user. The dual axis solar tracking system uses the Particle Swarm Optimization [PSO] to look at the parameters of the PI controller.

Song et al. (2014) proposed a day lighting system which consists of optical fibers and a solar tracking model. The tracking precision is better than 0.1 degree which reveals that the amount of overlap of the focal spot and the entrance face is more than 80%. The system consists of the concentration level of 2500 suns. The device consists of two feedback circles, coarse and fine adjustments due to which the system exhibits a good tracking performance. The optical transmission efficiency lies between 37% and 40% which is close to theoretical value of 42%.

Sungur (2009) built a dual axis solar tracking system using a programmable logic controller unit. The PLC program was administered according to the calculations of azimuth and altitude solar angles for which the azimuth and altitude angles of the sun were calculated over a period of one year, at every hour in a day. These calculated slope angles were used to guide the tracking system. The PLC program on the basis of these azimuth and altitude angle calculations controlled the motors by giving them analog signals and ensured that the PV panel remains normal to the sun's radiations. On comparing the output data with a similar fixed solar model, the dual-axis solar tracking system yielded 42.6% more energy.

Barker et al. (2013) proposed a low-profile 2-axis solar tracker with unique linkage geometry to minimize shadowing by the adjacent trackers. To minimize the installation costs of solar trackers the system was secured to the ground using ground screws. The design consisted of two coplanar and perpendicular linear actuators coupled with a single linkage arm and pivots. And this was experimented in order to enhance packing density in grid configuration to increase the output but on comparing it with existing mast-style trackers no significant change in shadow footprint was observed.

A detailed comparative study between the output of dual-axis solar tracking based PV panel and a fixed tilted PV panel was conducted by Yilmaz et al. (2015). A 10 W prototype for dual-axis system and fixed system was created for the comparison

Table 4
Design and performance of some dual-axis solar trackers.

S. No.	Author's Name	Design Implemented	System Performance	Reference
1.	Perini et al.	• Dual axis tracking system with linear Fresnel lens collector.	• Global efficiency is less than 20% due to optical losses. • Global efficiency increased to 55% after insulating with evacuated receiver.	Perini et al. (2017)
2.	Yao et al.	• Dual axis tracking system with declination clock mounting system.	• Average energy efficiency of normal tracking with respect to that of fixed PV is more than 23.6%.	Yao et al. (2014)
3.	Fathabadi	• Dual axis solar tracker with sensor & sensor less feature.	• The average captured solar energy with sensor feature is 35.22% in one year & that for sensor less is 24.59% in one year.	Fathabadi (2016)
4.	Hernandez et al.	• Dual axis sun tracker using mechatronic design & PV system driven by robotic sensor.	• It achieves a better performance than fixed as well as single axis mechanism.	Flores-Hernandez et al. (2017)
5.	Away & Ikhsan	• Dual axis solar tracker with three identical LDRs in tetrahedron shape.	• It has wide field of view, accuracy & effectiveness as compared with previous types of model.	Away and Ikhsan (2016)
6.	Abdallah & Nijmeh	• Dual axis solar tracker with PLC to control the motion of solar tracking system.	• Increment in total daily collection of about 41.34% as compared with that of 32° tilted fixed surface.	Abdallah and Nijmeh (2004)
7.	Khalifa & Mutawalli	• Study of thermal performance of two axis solar tracker with compound parabolic concentrator.	• CPC collector showed an increase in the collector energy of 75% when compared with identical fixed collector	Khalifa and Al-mutawalli (1998)
8.	Chen et al.	• Field programmable gate array [FPGA] based intelligent sun tracking system with the usage of NI9642 controller to integrate dual axis solar tracker with Maximum Power Point Tracker.	• This system is assist with MATLAB so that the system can be switched to dual axis solar tracker, one axis solar tracker & fixed solar panel according to the need of the user.	Chen et al. (2015)
9.	Song et al.	• A day lightning system which consists of optical fibers & solar tracking model. The device contains two feedback circles, coarse & fine adjustments due to which system exhibits good tracking performance.	• Optical transmiss- -ion efficiency lies between 37% & 40% which is close to theoretical value of 42%.	Song et al. (2014)
10.	Roth et al.	• Closed loop dual axis solar tracking system with four quadrant photo detectors & 2 small D.C. servo motors & a pyrheliometer for direct solar radiation measurement a z-80 processor.	• At solar irradiance below 140 W/m^2, the radiation falls nearly to zero but above this the system works fine.	Roth et al. (2004)
11.	Oner et al.	• Single spherical motor with the ability to Move the panel in both the directions is used.	• Panel output of spherical motor based PV panel was better than the fixed PV panel.	Oner et al. (2009)
12.	Zhang et al.	• Altitude-azimuth dual axis solar tracking mode is used as main tracking mode & time-based tracking system is used as the auxiliary support with battery, MCV, photosensitive sensors & temperature sensors for a solar streetlight active sun tracker.	• Tracking was done after a regular interval of 20 min saving energy & producing an average energy efficiency of about 36% in a year proving superiority of tracking mode.	Zhang et al. (2013)
13.	Sungur	• Dual axis solar tracking system using a PLC with a program based on the mathematical calculations of azimuth & altitude solar angles.	• This system yielded 42.6% more energy in comparison with a similar fixed solar module.	Sungur (2009)
14.	Barker et al.	• A low profile 2 axis solar tracker with unique linkage geometry (2 coplanar & perpendicular linear actuators coupled with a single linkage arm & pivots) was used to minimize the shading by adjacent trackers.	• On comparison with existing mast style trackers, no significant change in shadow footprint was observed.	Barker et al. (2013)

(*continued on next page*)

and the dual-axis system produced 34.02% more energy than the fixed one. 55.91 Wh energy was produced by the sun tracker system throughout the day whereas the fixed one managed to produce 41.71 Wh in a day. This paper also presents theoretical calculations to analyze parameters like solar radiation and angle of incidence.

Perini et al. (2017) proposed a dual axis solar tracking system with linear Fresnel lens collector. The performance analysis curve of the collector was designed for the temperatures between 40 °C

Table 4 (*continued*).

S. No.	Author's Name	Design Implemented	System Performance	Reference
15.	Yilmaz et al.	• Low prototype for dual axis system & fixed system was created for comparison & azimuth angles were calculated using MATLAB m-file.	• Dual axis system produced 34.02% more energy than the fixed one. Whole day production of panel involving tracking system was 55.91 Wh whereas fixed system produced a total of 41.71 Wh.	Yilmaz et al. (2015)
16.	Sinha & Chandel	• 6 different types of tracking system namely HAMA, HAWA, HADA, HACA, VACA & TA were compared with a fixed tilt system.	• The 2 axis tracking (TA) system was found to be more advantageous than others.	Sinha and Chandel (2016)
17.	Skouri et al.	• 3 pilot dual axis sun tracking system (LDR based, date & time based using screw nut actuators, date & time based using reduction gear units) were compared.	• Date & time based sun tracker using reduction gear units was more stable & accurate.	Skouri et al. (2016)
18.	Rahimi et al.	• A hybrid sun–wind tracking system using 2 actuators motors for solar tracking & 1 for wind tracking is built with a wind vane & wind tunnel for cooling purposes.	• In comparison with the fixed panel, solar tracking panel produces 39.43% more energy whereas a hybrid tracking system produces 49.83% more on a daily basis.	Rahimi et al. (2015)
19.	Al-Soud et al.	• A parabolic solar cooker with automatic 2-axes tracking system using PLC whose program is based on pre calculated solar angles is built.	• It can heat up the water to 90 °C when the maximum ambient temperature reaches 36 °C & allows food to be left in all day without burning.	Al-Soud et al. (2010)
20.	Abdollahpour et al.	They studied that an inexpensive dual-axis solar tracker with high accuracy for PV applications. Processing of images from a bar shadow was used to track sun. The system required no astronomical equipment to position sun and was independent of the geographical location and initial settings.	• Tracking system was successful in tracking the sun with an accuracy of about ±2%.	Abdollahpour et al. (2018)
21.	Seme et al.	• Two axis solar tracker with open loop control system.	• It produces more than 27% electric energy than the fixed system.	Seme et al. (2017)

and 90 °C. It was found that the global efficiency of the collector was less than 20%. It was so because of reflection, refraction and deflection in the Fresnel lenses which resulted in optical loss of the lens system with 47% of the total energy dissipated. Thermal radiation convection accounted for up to 6% of the total. In order to improve the global efficiency it was recommended to install an evaluated receiver and to insulate the recirculation system which could increase global efficiency up to 55%.

Usually in classic dual axis tracking mechanisms, 2 DC servo or stepper motors are used for the movement of the panel in both the respective directions but Oner et al. (2009) designed a dual-axis solar tracking system with a single spherical motor with the ability to move the panel in both the directions. Performance of the fixed tilted PV panel and dual-axis solar tracker with spherical motor based PV panel was compared. It was found that the panel output voltage for tracking mechanism was better than the fixed at all times of the day and particularly after 13:00 since after that the solar lights falling on the panel becomes denser.

Zhang et al. (2013) proposed an active sun tracker for solar streetlight with altitude-azimuth dual axis tracking mode as the main tracking system and time based tracking mode as the supporting system acting only at the time of special weather conditions like a rainy day. Reason for using auxiliary support tracking system is that the photo electric tracking mode cannot track the sun continuously as soon as the weather turns cloudy and rainy and thus giving rise to mal-operation. Since the time-based tracking system is not affected by the weather conditions and could fill in the gaps left by the sensor tracking mode, it was adopted as the auxiliary system. The switching between the two modes is automatic according to the weather conditions. Its tracking system comprises of solar panels, storage battery, MCV, photosensitive sensors, temperature sensors, stepping motors etc. To save the energy there was a setting time interval of 20 min. and the tracking devices tracked the sun periodically only after this interval (regardless of which kind of tracking was done). A model named available energy absorption model was built to study the energy efficiency which concluded that the average value of energy efficiency in a year is 36% proving superiority of tracking mode on the available energy absorption. The design and Performance of some dual-axis solar trackers is given in Table 4.

Yao et al. (2014) projected a tracker that employs a declination clock mounting system which locates the primary axis in east–west direction. On the basis of the mounting system, the normal tracking strategy is implemented for flat PV systems and daily adjustment strategies for Concentrating Solar Power (CSP) systems. The normal tracking strategy yields in less error when compared with pre-specified value. The daily adjustment strategy needs to adjust primary axis once in a day and secondary axis is rotated at a constant speed of 15°/h. Results of the accuracy test showed that the tracking error of normal tracking strategy was within 0.15°.

It has been found that the average energy efficiency of the normal tracking PV with respect to that of fixed PV is more than 23.6% and the result of average energy efficiency of the daily adjusted PV is more the 31.8%.

Fathabadi (2016) showed that a dual-axis tracker equipped with sensor less features has a tracking error of only 0.43° which is far less than other sensor less trackers. The dual axis tracker equipped with sensor is approximated with an error up to 0.14°. When the sensors are applied on the fixed PV panel at sun's

noon position, the average daily captured solar energy increases to 27.7% in winter, 32.5% in spring, 37.3% in autumn, 42.7% in summer and 35.22% during a whole year. For the sensor less setup on the fixed PV panel, these factors are less as 19.1% in winter, 22.4% in spring, 26.1% in autumn, 30.2% in summer and 24.59% in a year. The only drawback of solar tracking system with sensor is that it becomes expensive and more complicated.

4. Future scope and limitations

Solar power has been now considered as the fastest growing source of electricity generation. It is considered as a pollution free source of energy. In India, power distribution company BSES Yamuna has launched a pilot project to establish solar micro grids, which is emerging as one of the first Discoms in the country. These rooftop micro grids vary between 5 kW and 7 kW and have energy storage between 7 kWh and 10 kWh. It has been estimated that about 1245 l of diesel and 0.24 million units of electricity which costs up to Rs.20 Lakh can he saved on an annual basis by the solar micro grids while reducing 205 tonnes of CO_2 emission. This rooftop solar scheme aims to achieve total rooftop solar power generation capacity of 40,000 MW (Anon, 2019a). In Singapore it is expected that utility scale solar installations will reach 108 GW in 2019 and 119 GW in year 2020 (Anon, 2019b).

This area of research is growing very fast and hence many developments are taking place. Like the usage of Artificial Neural Networking in modeling different solar energy devices is leading to higher accuracy, higher generation capabilities and short computational time (Elsheikh and Haiou, 2019). Artificial neural network and fuzzy logics have owned the world today, these tools are being utilized in every field and so is here. Fuzzy logic controllers are being designed to obtain maximum power point tracking in a PV system (Farajdadian and Hassan Hosseini, 2019). Today cascade control algorithms are being used for high concentration photovoltaics which are capable of achieving a sun tracking error of 1′ (one minute) (Garrido and Díaz, 2016; Bahrami and Okoye, 2018; Bahrami et al., 2017, 2016). Scientists and researchers are working on the optimization of energy extraction and doing so, an approach based on deep learning, low cost and computer vision open hardware has been developed to curb limitations regarding cost and operational problems (Carballo et al., 2018; Okoye et al., 2018). In spite of many developments, this field still faces some impediments and hence more work in this field regarding operational efficiency, cost effectiveness and feasibility demands attention.

5. Conclusion

This study presents an overview on the advancements in the work of the solar tracking systems in the world and it emphasizes on the performance analysis of dual axis solar tracking systems equipped with different designs and techniques which have been evolved in recent years. Some conclusions drawn are stated below–

- Dual axis solar tracking systems generally prove to be more efficient than single axis and fixed counterparts.
- These systems also demand maintenance due to the presence of rotating components.
- These systems contain more complex design and control mechanism.
- The performance of the solar system depends on many physical factors and so does the choice of use of tracking.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

We are thankful to the administration of Ujjain Engineering College, Ujjain, AICTE and MHRD (NPIU-TEQIP-III), Government of India for providing kind support for carrying out this research work.

References

Abdallah, Salah, Nijmeh, Salem, 2004. Two axes solar tracking system with PLC control. Energy Convers. Manage. 45 (11–12), 1931–1939. http://dx.doi.org/10.1016/j.enconman.2003.10.007.

Abdelghani-Idrissi, M.A., Khalfallaoui, S., Seguin, D., Vernieres-Hassimi, L., Leveneur, S., 2018. Solar tracker for enhancement of the thermal efficiency of solar water heating system. Renew. Energy 119, 79–94. http://dx.doi.org/10.1016/j.renene.2017.11.072.

Abdollahpour, Masoumeh, Golzarian, Mahmood Reza, Rohani, Abbas, Zarchi, Hossein Abootorabi, 2018. Development of a machine vision dual-axis solar tracking system. Sol. Energy 169, 136–143. http://dx.doi.org/10.1016/j.solener.2018.03.059.

Ahmad, S., Shafie, S., Kadir, M.Z.A., 2013a. Power feasibility of a low power consumption solar tracker. Procedia Environ. Sci. 17, 494–502.

Ahmad, S., Shafie, S., Kadir, M.Z.A., Ahmad, N.S., 2013b. On the effectiveness of time and date based sun positioning solar collector in tropical climate: a case study in northern Peninsular Malaysia. Renew. Sustain. Energy Rev. 28, 635–642. http://dx.doi.org/10.1016/j.rser.2013.07.044.

Al-Addous, M., Dalala, Z., Class, C.B., Alawneh, F., Al-Taani, H., 2017. Performance analysis of off-grid PV systems in the Jordan valle. Renew. Energy http://dx.doi.org/10.1016/j.renene.2017.06.034.

Al-Naima, Fawzi, Yaghbian, N.A., 1990. Design and construction of a solar tracking system. Sol. Wind Technol. 7 (5), 611–617. http://dx.doi.org/10.1016/0741-983X(90)90072-A.

Al-Soud, Mohammed S., Abdallah, Essam, Akeyleh, Ali, Abdullah, Salah, Hrayhat, Eyad S., 2010. A parabolic solar cooker with automatic two axes Sun tracking system. Appl. Energy 87, 463–470. http://dx.doi.org/10.1016/j.apenergy.2009.08.035.

Ali, Ahmed I.M., Sayed, Mahmoud A., Mohamed, Essam E.M., 2018. Modified efficient perturb and observe maximum power point trackingtechnique for grid-tied pv system. Electr. Power Energy Syst. 99, 192–202. http://dx.doi.org/10.1016/j.ijepes.2017.12.029.

Anon, 2019a. https://energy.economictimes.indiatimes.com/news/renewable/discom-to-set-up-four-solar-microgrids-in-east-delhi/683848299.

Anon, 2019b. https://energy.economictimes.indiatimes.com/news/renewable/large-scale-solar-power-set-for-double-digit-growth-goldman-sachs/68404095.

Arlikar, Pratik, Bhowmik, Abhijit, Patil, Manoj, Deshpande, Amruta, 2015. Three dimensional solar tracker with unique sensor arrangement.international conference on smart technologies and management for computing. Commun. Controls Energy Mater. (ICSTM) 50, 9–513. http://dx.doi.org/10.1109/ICSTM.2015.7225470.

Away, Yuwaldi, Ikhsan, M., 2016. Dual-axis sun tracker sensor based on tetrahedron geometry. Autom. Constr. http://dx.doi.org/10.1016/j.autcon.2016.10.009.

Bahrami, Arian, Okoye, Chiemeka Onyeka, 2018. The performance and ranking pattern of PV systems incorporated with solar trackers in the northern hemisphere. Renew. Sustain. Energy Rev. 97, 138–151.

Bahrami, Arian, Okoye, Chiemeka Onyeka, Atikol, Ugur, 2016. The effect of latitude on the performance of different solar trackers in Europe and Africa. Appl. Energy 177, 896–906.

Bahrami, Arian, Okoye, Chiemeka Onyeka, Atikol, Ugur, 2017. Technical and economic assessment of fixed, single and dual axis tracking PV panels in low latitude countries. Renew. Energy 113, 563–579.

Barker, Laughlin, Neber, Matthew, Lee, Hohyun, 2013. Design of a low profile two-axis solar tracker. Sol. Energy 97, 569–576. http://dx.doi.org/10.1016/j.solener.2013.09.014.

Batayneh, Wafa, Batineh, Ahmad, Soliman, Ibrahim, Hafees, Saleh Abed, 2019. Investigation of single axis discrete solar tracking system for reduced actuations and maximum energy collection. Autom. Constr. 98, 102–109. http://dx.doi.org/10.1016/j.autcon.2018.11.011.

Bernal-Agustı´n, Jose´ L., Dufo-Lo´pez, Rodolfo, 2009. Simulation and optimization of stand-alone hybrid renewable energy systems. Renew. Sustain. Energy Rev. 13, 2111–2118. http://dx.doi.org/10.1016/j.rser.2009.01.010.

Braun, J.E., Mitchell, J.C., 1983. Solar geometry for fixed and tracking surfaces. Sol. Energy 31, 439–444. http://dx.doi.org/10.1016/0038-092X(83)90046-4.

Carballo, J.A., Bonilla, J., Berenguel, M., Jesú, Fernández-Reche, Giné, García, 2018. New approach for solar tracking systems based on computer vision, low cost hardware and deep learning. Renew. Energy http://dx.doi.org/10.1016/j.renene.2018.08.101.

Chen, Jui-Ho, Yau, Her-Terng, Hung, Tzu-Hsiang, 2015. Design and implementation of FPGA-based Taguchi-chaos-PSO Sun tracking systems. Mechatronics 25, 55–64. http://dx.doi.org/10.1016/j.mechatronics.2014.12.004.

Clifford, M., Eastwood, D., 2004. Design of a novel passive solar tracker. Sol. Energy 77 (3), 269–280.

cosmosmagazine, 2017. How solar cells turn sunlight into electricity. https://cosmosmagazine.com/technology/how-solar-cells-turn-sunlight-into-electricity (accessed 13 2019).

Cruz-Peragón, F., Casanova-Peláez, P.J., Díaz, F.A., Lopez-Garcia, R., Palomar, J.M., 2011. An approach to evaluate the energy advantage of two axes solar tracking systems in Spain. Appl. Energy 88, 5131–5142.

Elsheikh, Ammar H., Haiou, Zhang, 2019. Modeling of solar energy systems using artificial neural network:Acomprehensive review. Sol. Energy 180, 622–639, https://www.researchgate.net/publication/330637294_Modeling_of_solar_energy_systems_using_artificial_neural_network_A_comprehensive_review.

energy.gov, 2019. Cadmium telluride. https://www.energy.gov/eere/solar/cadmium-telluride accessed (17 2019).

energyinformative, 2012. Hybrid solar systems. https://energyinformative.org/grid-tied-off-grid-and-hybrid-solar-systems/ (accessed 14 2019).

Fan, Shuaiqi, Yang, Wanli, Hu, Yuantai, 2018. Adjustment and control on the fundamental characteristics of a piezoelectric PN junction by mechanical – loading. Nano Energy 52, 416–421. http://dx.doi.org/10.1016/j.nanoen.2018.08.017.

Farajdadian, Shahriar, Hassan Hosseini, S.M., 2019. Design of optical fuzzy controller to obtain maximum solar power generating system. Sol. Energy 182, 161–178.

Fathabadi, Hassan, 2016. Comparative study of two novel sensorless and sensor based dual-axis solar trackers. Sol. Energy 138, 67–76. http://dx.doi.org/10.1016/j.solener.2016.09.009.

Flores-Hernandez, D.A., Palomino-Resendiz, S., Lozada-Castillo, N., Luviano-Juarez, A., Chairez, I., 2017. Mechatronic design and implementation of a two axes Sun tracking photovoltaic system driven by robotic sensor. Mechatronics 47, 148–159, http://dx.doi.org/10.1016/j.mechatronics.2017.http://dx.doi.org/10.1016/j.rser.2014.11.09069009.014.

Garrido, Ruben, Díaz, Arturo, 2016. Cascade closed -loop control of solar trackers applied to HCPV systems. Renew. Energy 97, 689–696. http://dx.doi.org/10.1016/j.renene.2016.06.022.

geolounge, 2014. Latitude and longitude. https://www.geolounge.com/latitude-longitude (accessed 15 March).

Ghafoor, Abdul, Munir, Anjum, 2015. Design and economics analysis of an off grid PV system for household electrification. Renew. Sustain. Energy Rev. 42, 496–502. http://dx.doi.org/10.1016/j.rser.2014.10.012.

Ghenai, Chouki, Bettayeb, Maamar, 2019. Grid-tied solar PV/fuel hybrid power system for university building. Energy Procedia 159, 96–103. http://dx.doi.org/10.1016/j.egypro.2018.12.025.

Ghenai, Chaouki, Merabet, Adel, Salameh, Tareq, Pigem, Erolacolon, 2018. Grid-tied and stand-alone hybrid solar power system for desalination. Desalination 435, 172–180. http://dx.doi.org/10.1016/j.desal.2017.10.044.

Gholinejad, Mahdi, Bakhtiari, Amin, Bidi, Mokhtar, 2016. Efeects of tracking modes on the performance of a solar MED plant 380, 29-42. http://dx.doi.org/10.1016/j.desal.2015.11.015.

Hafez, A.Z., 2017. Tilt and azimuth angles in solar energy applications - A review. Renew. Sustain. Energy Rev. 77, 147–168. http://dx.doi.org/10.1016/j.rser.2017.03.131.

Jha, Shibani K., Puppala, Harish, 2017. Prospects of renewable energy sources in India: Prioritization of alternative sources in terms of energy index. Energy http://dx.doi.org/10.1016/j.energy.2017.03.110.

Kalogirou, Soteris A., 1996. Design and construction of one-axis Sun-Tracking system. Sol. Energy 57 (6), 465–469. http://dx.doi.org/10.1016/S0038-092X(96)00135-1.

Karafil, Akif, Ozbay, Harn, Kesler, Metin, Parmaksiz, Huseyin, 2015. Calculation of optimum fixed tilt angle of PV panels depending on solar angles and comparison of the results with the experimental study conducted in summer in Bilecik. Turley http://dx.doi.org/10.1109/ELECO.2015.7394517.

Khalifa, abdul-jabbar n., Al-mutawalli, salman s., 1998. Effect of two-axis sun tracking on the performance of compound parabolic of compound parabolic concentrators. Energy Convers. Manage. 39 (10), 1073–1079. http://dx.doi.org/10.1016/S0196-8904(97)10020-6.

Kumar, S., Bhattacharyya, B., Gupta, V.K., 2017. Present & future energy scenario in India. http://dx.doi.org/10.1007/s40031-014-0099-7.

Li, Guiqiang, Shittu, Samson, Diallo, Thierno M.O., Yu, Min, Zhao, Xudong, Ji, Jie, 2018. A review of solar photovoltaic-thermoelectric hybrid system for electricity generation. Energy http://dx.doi.org/10.1016/j.energy.2018.06.021.

matmatch, 2018. Photovoltaics : Materials used and how their efficiency and cost can be improved. https://matmatch.com/blog/solar-panels-materials-efficiency-cost/ (accessed 17 2019).

Moharram, K.A., Abd-Elhady, M.S., Kandil, H.A., El-Sherif, H., 2013. Influence of cleaning using water and surfactants on the performance of photovoltaic panels. Energy Convers. Manage. 68, 266–272. http://dx.doi.org/10.1016/j.enconman.2013.01.022.

Mousazadeh, Hossein, Keyhani, Alireza, Javadi, Arzhang, Mobli, Hossein, Abrinia, Karen, Sharifi, Ahmed, 2009. A review of priniciple and sun tracking methods for maximizing solar systems output. Renew. Sustain. Energy Rev. 13 (8), 1800–1818. http://dx.doi.org/10.1016/j.rser.2009.01.022.

Neville, 1978. Solar energy collector orientation and tracking mode. Sol. Energy 20, 7–11. http://dx.doi.org/10.1016/0038-092X(78)90134-2.

Numbi, B.P., Malinga, S.J., 2017. Optimal energy cost and economic analysis of a residential grid interactive solar PV system-case of eThekwini municipality in South Africa. Appl. Energy 186, 28–45. http://dx.doi.org/10.1016/j.apenergy.2016.10.048.

Nuwayhid, R.Y., Mrad, F., Abu-Said, R., 2001. The realization of a simple solar tracking concentrator for university research aplications. Renew. Energy 24, 207–222. http://dx.doi.org/10.1016/S0960-1481(00)00191-9.

Okoye, Chiemeka Onyeka, Bahrami, Arian, Atikol, Ugur, 2018. Evaluating the solar resource potential on different tracking surfaces in Nigeria. Renew. Sustain. Energy Rev. 81, 1569–1581.

Oner, Yusuf, Cetin, Engin, Ozturk, Harun Kemal, Yilanci, Ahmet, 2009. Design of a new three degree of freedom spherical motor for photovoltaic-tracking systems. Renew. Energy 34, 2751–2756. http://dx.doi.org/10.1016/j.renene.2009.04.025.

Parmar, N.J., Parmar, A.N., Gautam, V.S., 2015. Passive solar tracking system. Int. J. Emerg. Technol. Adv. Eng. 5, 138–145.

Paulo, Alex Fabianne de, Porto, Geciane Silveira, 2018. Evolution of collaborative networks of solar energy applied technologies. J. Cleaner Prod. http://dx.doi.org/10.1016/j.jclepro.2018.08.344.

Perini, Simoni, Tonnellier, Xavier, King, Peter, Sansom, Christopher, 2017. Theoretical and experimental analysis of an innovative dual-axis tracking linear Fresnel lenses concentrated solar thermal collector. Sol. Energy 153, 679–690. http://dx.doi.org/10.1016/j.solener.2017.06.010.

Poulek, V., 1994. New low cost solar tracker. Sol. Energy Mater. Sol. cells 33, 287–291. http://dx.doi.org/10.1016/0927-0248(94)90231-3.

Pritam Satsangi, K., Bhagwan Das, D., Sailesh Babu, G.S., Saxena, A.K., 2018. Performance analysis of grid interactive solar photovoltaic plant in India. Energy Sustain. Dev. 47, 9–16. http://dx.doi.org/10.1016/j.esd.2018.08.003.

pveducation, 2019. Fixed or tracking array. https://pveducation.com/solar-concepts/fixed-or-tracking-array/ (accessed 15 2019).

Rahimi, Masoud, Banybayat, Meisam, Tagheie, Yaghoub, Valeh-e-Sheyda, Peyvand, 2015. An insight on advantage of hybrid Sun-wind-tracking over Sun-tracking. Energy Convers. Manage. 105, 294–392. http://dx.doi.org/10.1016/j.enconman.2015.07.086.

Roth, P., Georgiev, A., Boudinov, H., 2004. Design and construction of a system for Sun-tracking. Renew. Energy 29, 393–402. http://dx.doi.org/10.1016/S0960-1481(03)00196-4.

Rubio, F.R., Oretga, M.G., Gordillo, F., Lopez-Martinez, M., 2007. Application of new contro strategy for Sun tracking system. Energy Convers. Manage. 48, 2174–2284. http://dx.doi.org/10.1016/j.enconman.2006.12.020.

Seme, Sebastijan, Srpcic, Gregor, Kavsek, Domen, Bozicnik, Stane, Letnik, Tomislv, Praunseis, Zdrravko, Stumberge, Bojan, Hadziseimovic, Miralem, 2017. Dual-axis photovoltaic tracking system-design and experiment investigation. Energy http://dx.doi.org/10.1016/j.energy.2017.05.153.

Sharaf Eldin, S.A., Abd-Elhady, M.S., Kandil, H.A., 2016. Feasibilty of solar tracking systems for PV panels in hot and cold regions. Renew. Energy 85, 228–233. http://dx.doi.org/10.1016/j.renene.2015.06.051.

Sidek, M.H.M., Hasan, W.Z.W., Ab. Kadir, M.Z.A., Shafie, S., Radzi, M.A.M., Ahmad, S.A., Marhaban, M.H., 2014. GPS based Portable solar axis tracking system using astronomical equations. http://dx.doi.org/10.1109/PECON.2014.7062450.

Sinha, Sunanda, Chandel, S.S., 2016. Analysis of fixed tilt and Sun tracking photovoltaic -micro wind based hybrid power systems. Energy Convers. Manage. 115, 265–275. http://dx.doi.org/10.1016/j.enconman.2016.02.056.

Skouri, Safa, Ali, Abdessalem Ben Haj, Bouadila, Salwa, Salah, Mohieddine Ben, 2016. Design and construction of Sun tracking systems for solar parabolic concentrator displacement. Renew. Sustain. Energy 60, 1419–1429. http://dx.doi.org/10.1016/j.rser.2016.03.006.

Solar Power World, 2016. https://www.solarpowerworldonline.com/2016/05/advantages-disadvantages-solar-tracker-system/ (Accessed on 12 2019).

Solarpowerworldonline, 2015. What are some common types of solar PV and storage installations. https://www.solarpowerworldonline.com/2015/10/what-are-some-common-types-of-solar-pv-and-storage-installations/ (accessed 13 2019).

Song, Jifeng, Zhu, Yong, Jin, Zhou, Yang, Yongping, 2014. Daylighting system via fibers based on two-stage sun-tracking model. Sol. Energy 108, 331–339. http://dx.doi.org/10.1016/j.solener.2014.07.021.

Stamatescu, Iulia, Fagarasan, Ioana, Stamatescu, Grigore, Arghira, Nicoleta, Iliescu, Sergiu Stelin, 2014. Design and implementation of a solar tracking algorithm. Procedia Eng. 69, 500–507. http://dx.doi.org/10.1016/j.proeng.2014.03.018.

Stanciu, C., Stanciu, D., 2014. Optimum tilt angle for flat plate collectors all over the world – a declination dependence formula and comparisons of three solar radiation models. Energy Convers. Manage. 81, 133–143.

Sultan, Manzoor, Wu, Junying, Aleem, Fazale, Imran, Mohammad, 2018. Cost and energy analysis of a grid tie solar system synchronized with utility and fossil fuel generation with major issues for the attenuation of solar power in Pakistan. Sol. Energy 174, 967–975. http://dx.doi.org/10.1016/j.solener.2018.09.052.

Sun, Ā.J., Wang, R., Hong, H., Liu, Q., 2016. An optimized tracking strategy for small-scale double axis parabolic trough collector. Appl. Therm. Eng. http://dx.doi.org/10.1016/j.applthermaleng.2016.10.187.

Sungur, Cemil, 2009. Multi-axes Sun-tracking system with PLC control for photovoltaic panels in Turkey. Renew. Energy 34, 1119–1125. http://dx.doi.org/10.1016/j.renene.2008.06.020.

Talebizadeh, P., Mehrabian, M.A., Abdolzadeh, M., 2011. Prediction of the optimum slope and surface azimuth angles using the Genetic Algorithm. Energy Build. 43, 2998–3005.

Theconomictimes, 2019. https://energy.economictimes.indiatimes.com/news/renewable/india-projected-to-be-on-track-to-achieve-paris-climate-agreement-target-us-expert/68229428 (accessed on 4 2019).

Wikipedia, 2019. Thin-film solar cell. https://en.m.wikipedia.org/wiki/Thin-film_solar_cell (accessed 17 2019).

Wikipedia, 2019a. Solar azimuth angle. https://en.wikipedia.org/wiki/Solar_azimuth_angle (accessed 15 2019).

Wikipedia, 2019b. Solar photovoltaics. https://en.m.wikipedia.org/wiki/Concentrator_photovoltaics (accessed 17 2019).

Yao, Yingxue, Hu, Yegaung, Gao, Shengdong, Yang, Gang, Du, Jinguang, 2014. A multipurpose dual-axis solar tracker with two tracking strategies. Renew. Energy 72, 88–98. http://dx.doi.org/10.1016/j.renene.2014.07.002.

Yilmaz, Saban, Ozcalik, Hasan Riza, Dogmus, Osman, Dincer, Furkan, Akgol, Oguzhan, Karaaslan, Muharrem, 2015. Design of two axes Sun tracking controller with analytically solar radiation calculations. Renew. Sustain. Energy 43, 997–1005. http://dx.doi.org/10.1016/j.rser.2014.11.090.

Zhang, Peng, Zhou, Gongbo, Zhu, Zhencai, Li, Wei, Cai, Zhixiong, 2013. Numerical study on the properties of an active Sun tracker for solar streetlight. Mechatronics 23, 1215–1222. http://dx.doi.org/10.1016/j.mechatronics.2013.08.007.

Zhong, H., Li, G., Tang, R., Dong, W., 2011. Optical performance of inclined southern-north axis three-positions tracked solar panels. Energy 36, 1171–1179.