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Solar tracking systems: Technologies and trackers drive types – A review

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ABSTRACT

This paper presents a comprehensive review on solar tracking systems and their potentials in solar energy applications. The paper overviews the design parameters, construction, types and drive system techniques covering different usage application. There are two main solar tracking systems types that depending on their movement degrees of freedoms are single axis solar tracking system and dual axis solar tracking system, which are addressed in the recent studies. The solar tracker drive systems encompassed five categories based on the tracking technologies, namely, active tracking, passive tracking, semi-passive tracking, manual tracking, and chronological tracking. The paper described the various designs and components of the tracking systems. There are 42.57% of the studies discussed and presented single axis tracking systems while 41.58% of these studies to the dual axes tracking systems. In the recent research studies, the most common solar tracker drive type was active tracker by 76.42% usage in applications while in the second most impact type is the chronological solar tracker by 7.55%. Furthermore, in the solar tracking techniques, Azimuth and altitude tracking achieved 16.67% in usage, Horizontal tracking by 16.67%, Azimuth tracking by 10%, and polar tracking by 4.44%.

1. Introduction

The solar tracking system plays an important role in different solar energy applications where its benefits not only exist in the power and efficiency gains and increase compared to the fixed systems, but also in the economic analyses of the large-scale solar energy applications. The systems are oriented with optimal tilt angles towards the equator from the horizon to maximize the solar radiation affects on the solar collectors and panels. The tracking angles depend on the site latitude and climatic conditions. There are two main solar tracking systems types that depend on the movement degree of freedom are single axis solar tracking system and dual axis solar tracking system. Several sun tracking systems are evaluated and showed to keep the solar panels, solar concentrators, or other solar applications as the recent studies of single axis tracking [1–43], dual axis tracking [44–85], single and dual axis tracking [86–107] with respect to the tracking systems types. A single axis solar tracking system is a technique to track the sun from one side to another using a single pivot point to rotate. This system has main three types: horizontal, vertical, and tilted single axis tracking system. The main CSP applications of the single axis tracker are parabolic trough and linear Fresnel solar systems. The main disadvantage of the single axis tracking system is that it can only track the sun during the daily movement and not the yearly movement, and during the cloudy days, the efficiency of the tracking system is reduced by a large amount due to the rotation around only one-axis. A dual axis solar tracking system is a technique that tracks the sun in two different axes using two pivot points to rotate. Solar tracker system in this type usually has both horizontal and vertical axes. One of the most important applications to dual axis tracker are CSP applications and especially solar dish and solar tower systems where the long distance between the heliostat reflectors and the receiver point concentration lead to angle errors in the results.

The solar tracker drive systems are classified into five types based on their tracking technologies, namely, active tracking, passive tracking, semi-passive tracking, manual tracking, and chronological tracking [1–90,92–96,98–100,108–112]. Active solar tracking system is the system that determines the position of the sun path in the sky during the day with the sensors. These sensors trigger the motor or actuator to move the drive system to the system towards the sun throughout the day. If the solar radiation beams are not perpendicular on the solar tracking system, then this will made a difference in light intensity on one sensor as compared to another leading to act the tracking system to be perpendicular on the sunlight beams. Active tracking system sorted with different control types as microprocessor-based, electric-optical sensor-based, date and time methods, and auxiliary PV cells [64,113]. Active tracking systems using microprocessor and electric-optical

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Nomenclature

b	The axis that parallel to the earth surface
$B-1$	First mirror of the solar box cooker
$B-2$	Second mirror of the solar box cooker
$CTES, ba$	Thermal energy storage cost at the balance point, $
Csf	Cost of solar field, $/m^2
H	Height of the shading plate, m
i	The cosine of incidence angle
L	Dual booster mirror solar cooker length, m
$L1$	Distance of the photosensing element from the plate, m
r	The tracking axis
S	Sun ray vector
u	The third orthogonal axis
W	Dual booster mirror solar cooker width, m
Wa	Solar hour angle, °
Y	Azimuth, °

Greek Symbols

α	Altitude angle, °
α_w	Azimuth angle, °
δ	Declination, °
$\theta 1$	Incidence angle of solar rays on the tracked panel, °
θi	Incidence angle, °
βin	Inclination of booster mirror B-1, °
θin	Inclination of booster mirror B-2, °
ϕ	Latitude angle, °
θL	Longitudinal incidence angle, °
$\Delta\eta track$	Loss of optical efficiency, %
γ	Orientation of the still, °
βp	Pyramidal sensors angle, °
ψrim	Rim angle, °
θs	Solar incident angle with respect to PV normal vector, °
θz	Solar incident zenith angle, °
βs	Stopping angle of tracker, °
θr	The amount of rotational angle about EE' axis measured from OV axis, °
βr	The amount of rotational angle about OV axis measured from OR axis, °
ρt	Thickness
β	Tilt angle, °
$\beta 1$	Tilt-angle of vertical-axis tracked solar panels with respect to the horizon, °
ΔJ	Tracking advantage, %
ρ	Tracking angle, °
θT	Transverse incidence angle, °

Acronyms

AADAT	Azimuth - Altitude Dual Axis Tracker
ASGHT	Asymmetric Greenhouse Type Still
CPV/T	Concentrated Photovoltaic Thermal
CSP	Concentrating Solar Power
DOF	Degree of Freedom
FKE	Faculty of Electrical Engineering
FLC	Fuzzy Logic Controller
FPC	Flat Plate Collector
FPGA	Field-Programmable Gate Array
ISNA	Inclined South-North Axis
ISNA-3P	Inclined South-North Axis - Three Positions
ISN-axis	Inclined South-North Single-Axis
LDR	Light Dependent Resistor
LFMSC	Linear Fresnel mirror solar concentrator
MED	Multi Effect Distillation
NISE	National Institute of Solar Energy
PID	Proportional Integral Derivative
PLA	Programmable Logic Array
PLC	Programmable Logic Control
PMDC	Permanent Magnet Direct Current
PMMA	Poly Methyl Methacrylate
PTC	Parabolic Trough Concentrator
PV	Photovoltaic
PVGCP	Photovoltaic Grid-Connected Plants
RSM	Reluctance Stepper Motor
RTC	Real Time Clock
SC	Spherical collector
SIST	Sensor Independent Solar Tracking
SMA	Shape Memory Alloy
SOG	Silicon of Glass
SOP	Slope of Panel
SPSTC	Semi-Passive Solar Tracking Concentrator
UTeM	Universiti Teknikal Malaysia
VSAT	Vertical Single Axis Tracker

sensors are used at least two photoresistors or PV cells. A comparison between the output signals of the two variables parameters is conducted, and, subsequently, send signal of the difference between them to the drive motor. In solar tracking systems with auxiliary bifacial solar cells, the cells trigger the drive system to move to the desired position. At cloudy days, this system is not accurate where the sensors cannot made a decision due to the low solar irradiance intensity difference between the sensors [64]. Solar power arrays play an important role in the design of the solar tracking systems with high precision designed systems. In addition, due to the large scale and widely use of PV systems for different applications, this type of solar tracking systems are widely used [114]. Passive tracking system is one of the solar tracking systems which depend on the thermal expansion in materials or an imbalance in pressure between two points at both ends of the tracker, where usually these materials as a fluid (liquid or gas). The passive solar tracking system relies on a low boiling point compressed gas fluid, which cause the structure of the tracker to move to an imbalance. A semi-passive tracking system is a technique where the solar tracking concentrator can track the sun and keep the sun's rays perpendicular to the absorber's cross-sectional area with a minimal mechanical effort and reduced movement for sun tracking. The system is consisted of a micro-heliostat array, a Fresnel lens and a receiver. Manual solar tracker is a method where the system can track the sun angle from season to season with manual tilt angle changing per seasons using a manual gear for ease of the system construction and maintenance. One of the significant advantages of the manual tilt angle axis as the secondary axis in the dual-axis tracking systems is cheaper than used in the previous types by implementing a second motor. A chronological solar tracking system is a time-based tracking system where the system collector or module moves with a fixed rate and a fixed angle throughout the day as well for different months. The motor or actuator is controlled to rotate at the low rate (15° per hour approx.). One of the main advantages of this system, which is more energy efficient because no energy losses at this tracking calibration due to low tracking error [88].

The main aim of this study is to review the solar tracking systems methods to decide which the optimum type, application, and the design for the solar systems. In Section 2, the historic overview of the solar tracking systems are described. The new techniques of the solar tracking systems are discussed in Section 3. In Section 4, the solar tracking systems types are described, as well as introduced the solar trackers drive types in Section 5. Finally, the conclusion is summarized in Section 6.

2. Historic overview of the solar tracking systems

The first active tracking systems showed in 1975, the system presented by McFee, which is an algorithm used to calculate the total power in a central receiver of a solar power system and determine the distribution of flux density in it. The error tolerance of the position of the sun was between 0.5° to 1°. Active tracking system sorted with different control types as microprocessor-based, electric-optical sensor-based, date and time methods, and auxiliary PV cells [64,113].

Zogbi and Laplaze [115] constructed dual-axis tracking system with two angles (azimuth and elevation) in 1984 using four electric-optical sensors, which placed in four quadrant formed using two rectangular plans with cross one another in a line. In order to compare the signals received from the sensors in each pair, an amplifier and other electronics components in the tracking control circuit are used. Then operates the two tracking motors using the signal received, and, at the beginning of the night, the system reset to its initial position. The motor is operated by an amplifier when the output of one of the sensors is greater than the threshold set. Rumala [116] presented a close loop control tracking system depending on the shadow method in 1986. Four photoresistors sensors are placed on a rigid platform, which has two articulated arms powered by engine's camshaft. The photoresistors are under a pair of cylinders mounted back to back East-West (E-W) and North-South (N-S). The control circuit is a signal conditioning circuit using a low pass filter, which feed an amplifier. It sends the signals to drive a servomotor for tracking and aligning the system through the difference of detected solar radiation, and, during the night, the system remains at the same position until sunset then autostart in the morning.

Kalogirou [117] presented a single-axis tracking system using three light dependent resistors (LDR) for the first time in 1996. The first LDR detects the focus state of the collector while the second and third LDRs discriminate the information between day and night and detects the presence or absence for shadowing. An electronic circuit received the signals from the output of the three LDR that triggers a low speed 12V/DC motor. Fig. (1.a) shows electro-optical sensors control signal where differential signal occurs to drive a motor by differential illumination until the illumination become equal between the two sensors. To increase the photocurrent sensitivity, the photo-resistors added on tilted surfaces as shown in Fig. (1.b). Fig. (1.c) shows a collimating tube to prevent diffuse radiation, which used as the shading device to PV applications [114]. Khalifa and Al-Mutawalli [118] showed dual-axis solar tracking system on a parabolic concentrator to improve the thermal of it where the tracking system is designed to track the sun every 3 min with respect to horizontal plane and 4 min with respect to the vertical plane.

One of the first passive tracking systems developed by Zomewords, which is an American company since 1969 [119]. Another passive tracking system is developed using shape memory alloy (SMA) based on axis actuators by Poulek in 1994, where SMA deformed at low operation temperatures range (below 70°C), and when it is heated above a certain specific temperature, SMA return to its original shape and SMA actuator operates as a heat engine during the thermal cycles. In addition, efficiency of SMA actuators is (~2%) compared to bimetallic actuators [120]. The best geographic locations to use the solar passive tracking systems near the equator due to the minimum variation in azimuth and elevation angles, high solar irradiance, and it can be useful to both high power generation and isolated applications. However, there are some disadvantages for this type, namely, low efficiency, not accurate, and where the system depends on thermal expansion process. Moreover, in case of bad and adverse weather conditions, the tracking system is not propped.

3. Overview of the solar tracking systems: types and components

There are number of studies and researches that were carried out in order to find the best performance of solar tracking system areas around the world, and others in a comparison between different locations. Fig. 2 shows solar tracking system studies during the years and we can conclude there are significant interest to the topic in the last five years. The application of tracking systems has been widely investigated. A number of studies were carried out to apply solar tracking systems that showed, constructed and simulated the tracking system in different applications in certain areas and countries around the world as shown in Fig. 3, such as, Algeria [27,68,96], Australia [42], Queensland, Australia [29], Bangladesh [64,93], Brazil [89,91], Canada [95], Montreal, Canada [52], China [1,6,11,16,19,55,76,92,97,110], Changdu, Xizang, China [86], Heilongjiang Province, China [57], Macau, China [58], Egypt [40,85,98,121–125], Aswan-Egypt [108], Estonia [35], Germany [39], Berlin-Germany, Stuttgart-Germany [108], Greece [88], Athens, Greece [44], Cyprus, Greece [41], India [4,13,14,24,47,50,56,62,72], Kolaghat, India [30], Pune, India [26], Indonesia [21], Iran [81], Tehran, Iran [87], Isfahan, Iran [7], Italy [15,33,71,94,100], Japan [34], Jordan [36,69,77,78], Kenya [38], Korea [73], Republic of Korea [20], Lebanon [83], Malaysia [2,5,12,28,31,51,66,70,82], Mexico City [18], México [61], Myanmar [65], Nigeria [43,46], Pakistan [22,23,48], Portugal [79], Romania [17,60,109], Slovenia [75], South Africa [63], Bloemfontein, South Africa [90], South Korea [53], Seoul, South Korea [45], Spain [9,10,32,74], Sri Lanka [3], Taiwan [37], Taipei, Taiwan [25], Tunisia

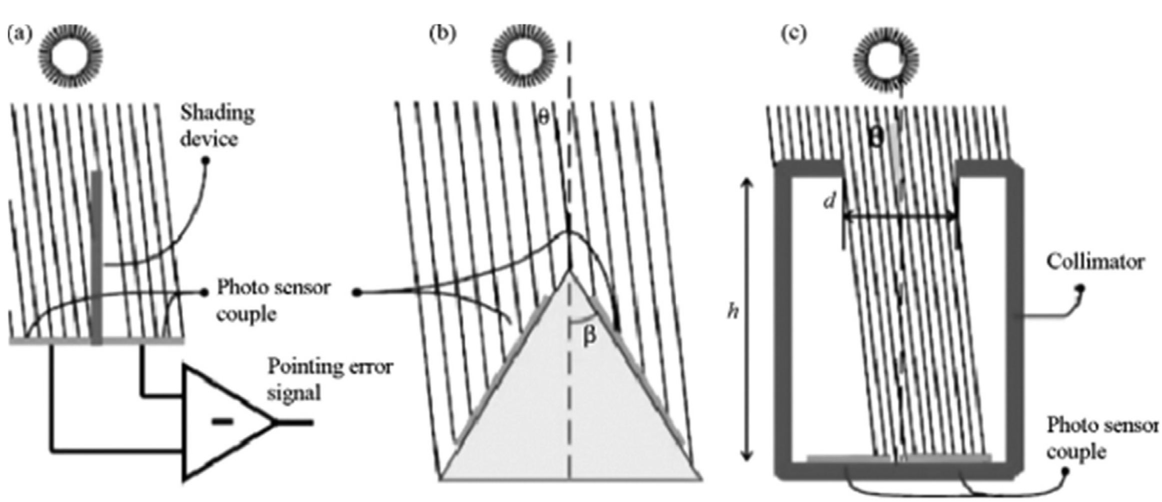


Fig. 1. Single-axis tracking system using three light dependent resistors (LDR) [114].

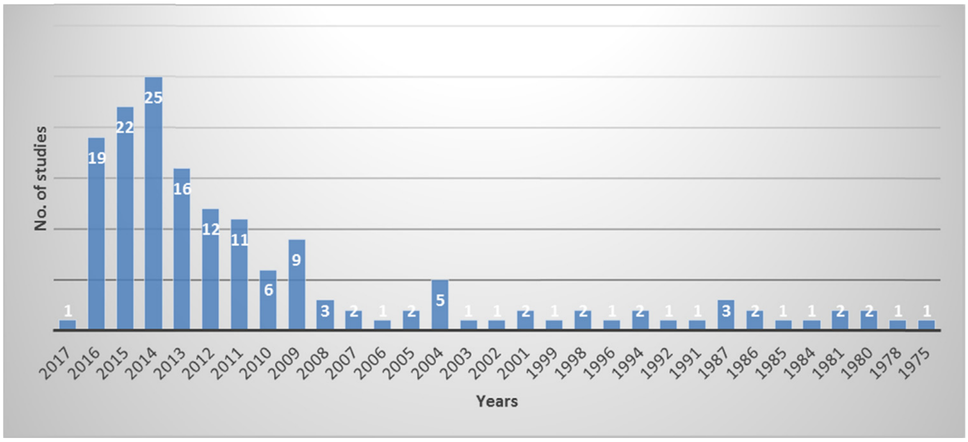


Fig. 2. Solar tracking system studies during the years.

[59], Turkey [54], United Kingdom [49], USA [80,99,126], Arizona, USA [67], Florida, USA [8], Thailand, USA [84].

There are two main solar tracking systems types that depend on the movement degree of freedom are single axis solar tracking system and dual axis solar tracking system. Several sun tracking systems are evaluated and showed to keep the solar panels, solar concentrators, or other solar applications as the recent studies of single axis tracking [1–43], dual axis tracking [44–85], single and dual axis tracking [86–100] with respect to the tracking systems types. Table (1) shows solar tracking systems specifications data in the recent studies and all details about the systems types, the drive mode techniques, and applications. Fig. 4 shows there are 42.57% of the studies discussed and presented single axis tracking systems while 41.58% of these studies to the dual axes tracking systems.

The solar tracker drive systems are classified into five types based on their tracking technologies, namely, active tracking, passive tracking, semi-passive tracking, manual tracking, and chronological tracking. The tracker drive types are showed and analysed in the recent studies: active [1,3–13,15,16,18,19,21,22,24–28,30,32–37,39–56, 58–60,62–65,67–90,92–96,98–100,108–110], chronological [2,31], manual [38], active (normal tracking), manual (daily adjustment on primary axis) [57], active, manual [20], active, chronological [66], passive [14,17,23,29,111], and semi-passive [61,112]. Fig. 5 shows the most common solar tracker drive type, was active tracker by 76.42% usage in applications while in the second most impact type is the chronological solar tracker by 7.55%.

The recent studies showed many special types under the main two types: a single-axis tracking - a north-south axis [42], azimuth tracking [7,11,13,16,20,22,25,36,38], horizontal tracking [2–6,8,12,21,24, 26–28,31,33,37], polar tracking [15,17,30,69], vertical tracking [14], north–south axis tracking [35], dual axis tracking [44,45,61,62, 77–81,84,85], azimuth and altitude tracking [48–51,54,55,58, 60,64,66,68,70–72,83], azimuth and elevation tracking [56,59,63,98], azimuth-Tilt tracking [65,74,75], horizontal-vertical tracking [46,67], azimuth tracking, two axis tracking [95], azimuth, azimuth and altitude [91], azimuth tracking tilted-wick [34], azimuth-elevation and tilt-roll tracking mechanism [82], tip-tilt, azimuth-altitude [93], polar axis tracking, E-W tracking, N-S tracking [87], polar tracking, azimuth-altitude [94], polar-axis tracking and two-axis tracking [99], N–S horizontal tracking, E–W horizontal tracking, N–S tilted tracking [86], N–S tracking, fixed tilt concentrator [10], vertical and inclined tracking [96], VSAT, AADAT, azimuth-altitude [88], dual axis sun tracking; vertical single axis sun tracking [97], E-W axis with slope variable, N-S tracking with slope variable about tilt yearly [18], horizontal E-W axis, horizontal N-S axis, fixed slope rotated about a vertical axis, N-S axis - parallel to the Earth's axis, two axis tracking [89], vertical single axis tracking, horizontal south-north axis and eat-west axis sun tracking, 2-axis sun-tracking [92], inclined axis tracking system, vertical axis tracking system, dual axis tracking system [90], declination-clock mounting with two rotation axes: primary axis, located in E-W and secondary axis, perpendicular to the primary axis and able to rotate around it [57], the single-axis tracking with vertical axis, fixed slope and variable azimuth and the seasonal tracking mode where the collector slope is changed twice per year [41], bidirectional solar azimuth tracking with sliding axle [19], new rotatable axis tracking system [110], novel one dimensional tracking mechanism [23], and 2-DOF parallel robot (U-2PUS parallel robot) [100]. Fig. 6 shows the percentage of the solar tracking techniques in the recent studies, where Azimuth and altitude tracking achieve 16.67% in usage, Horizontal tracking by 16.67%, Azimuth tracking by 10%, and polar tracking by 4.44%.

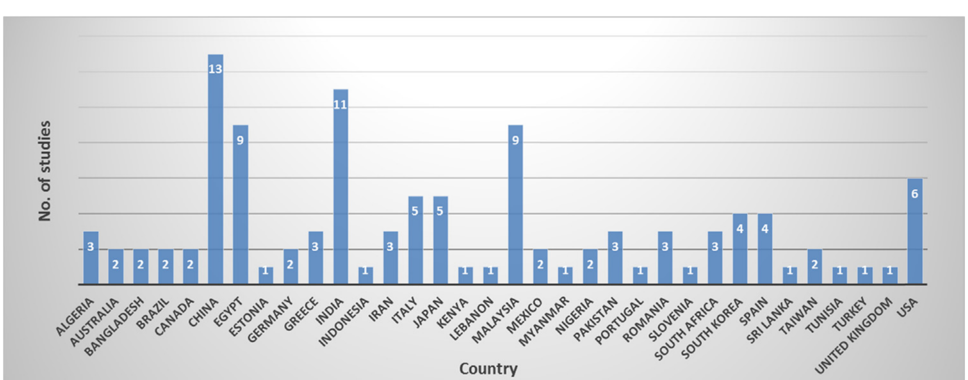


Fig. 3. Solar tracking systems studies in various countries.

Table 1
Solar tracking specifications data in the recent studies.

Ref.	Authors	Year	Country & Location	Solar Tracking Method (Single or Dual)	Solar Tracking Mode (Active, Passive, Manual)	Solar Tracking Type	Tracking Application	Research (T, E, S, or A)[a]
[1]	Zhao et al.	2016	China	Single	Active		Parabolic trough collector	T
[86]	Wu et al.	2016	Changdu, Xizang, China	Single, Dual	Active	N–S horizontal tracking, E–W horizontal tracking, N–S tilted tracking	Solar parabolic trough	T
[44]	Fathabadi	2016	Athens, Greece	Dual	Active	Dual axis	Photovoltaic systems	E
[45]	Hong et al.	2016	Seoul, South Korea	Dual	Active	Dual axis	Smart photovoltaic blind	T
[87]	Gholinejad et al.	2016	Tehran	Single, Dual	Active	Polar axis tracking, E-W tracking, N-S tracking	Freshwater production of a solar multi effect distillation (MED) plant	T
[47]	Parthipan et al.	2016	India	Single, Dual	Active		Paraboloidal dish	E
[2]	Roong and Chong	2016	Malaysia	Single	Chronological	Horizontal	Solar panel	E
[3]	Basnayake et al.	2016	Sri Lanka	Single	Active	Horizontal	Photovoltaic Module	T, S
[4]	Kumar N et al.	2016	India	Single	Active	Horizontal	Photovoltaic system	E
[5]	Theebhan et al.	2016	Malaysia	Single	Active	Horizontal	Solar thermal collectors, solar dish	E
[6]	Wang et al.	2016	China	Single	Active	Horizontal	Parabolic trough solar concentrator	E
[48]	Vijayalakshmi	2016	Pakistan	Dual	Active	Azimuth and altitude	Photovoltaic module	E
[49]	Gaafar and Zobaa	2016	United Kingdom	Dual	Active	Azimuth and altitude	Parabolic trough collector	E
[50]	Bhaskar and Yuvaraj	2016	India	Dual	Active	Azimuth and altitude	Photovoltaic module to solar powered vehicle	E
[7]	Avarand and Pirmoradian	2016	Isfahan, Iran	Single	Active	Azimuth	Photovoltaic panels	T
[8]	Moradi et al.	2016	Florida, USA	Single	Active	Horizontal	Photovoltaic system	E, A
[51]	Gitan et al.	2015	Malaysia	Dual	Active	Azimuth- Altitude	Solar collector to solar updraft tower power plant	T
[9]	Sallaberry et al.	2015	Spain	Single	Active		Parabolic trough collector (medium-temperature)	T, E
[52]	Quesada et al.	2015	Montreal, Canada	Dual	Active		PV systems	T, E
[10]	Sallaberry et al.	2015	Spain	Single	Active	N–S tracking, Fixed tilt concentrator	Concentration solar collector for domestic hot water	T, E
[11]	Li et al.	2015	China	Single	Active	Azimuth tracking	Solar collector	T
[100]	Cammarata	2015	Italy	Single, Dual	Active	2-DOF parallel robot (U − 2PUS parallel robot)	PV system	T
[53]	Hussain and Lee	2015	South Korea	Dual	Active		The CPV/T system was based on the union of 8 triple junction solar cells, 8 SOG Fresnel lenses	E
[12]	Soon et al.	2015	Malaysia	Single	Active	Horizontal	Photovoltaic (PV) panel	E
[13]	Patel et al.	2015	India	Single	Active	Azimuth	Solar panel	S
[14]	Parmar et al.	2015	India	Single	Passive	Vertical	Photovoltaic modules	E
[88]	Panagopoulos et al.	2015	Greece	Single, Dual	Active	VSAT, AADAT, Azimuth-Altitude	Photovoltaic systems	S
[54]	Yılmaz and Kentli	2015	Turkey	Dual	Active	Azimuth and altitude	Photovoltaic system	E
[55]	Chen et al.	2015	China	Dual	Active	Azimuth and altitude	Solar dish	T
[15]	Lazaroiu et al.	2015	Italy	Single	Active	Polar	Photovoltaic system	E
[56]	Das et al.	2015	India	Dual	Active	Azimuth-Elevation	Photovoltaic system	E
[16]	Huang et al.	2014	China	Single	Active	Azimuth	Linear Fresnel solar concentrator	T
[58]	Su et al.	2014	Macau, China	Dual	Active	Azimuth- Altitude	Concentrated PV thermal system	T, E
[59]	Bentaher et al.	2014	Tunisia	Dual	Active	Azimuth- Elevation	PV, Parabolic concentrator	T, E
[60]	Stamatescu et al.	2014	Romania	Dual	Active	Azimuth- Altitude	PV panel	E
[17]	Neagoe et al.	2014	Romania	Single	Passive	Polar	Flat plate collectors	E
[18]	Gutiérrez-Castro et al.	2014	Mexico City	Single	Active	E-W axis with slope variable, N-S tracking with slope variable about tilt yearly	Solar heating system for a thermophilic anaerobic digester (flat solar collector)	T
[19]	Song et al.	2014	China	Single	Active	Bidirectional solar azimuth tracking with sliding axle	PV for building integration	E
[90]	Vermaak	2014	Bloemfontein, South Africa	Single, Dual	Active	Inclined axis tracking system, Vertical axis tracking system, Dual axis tracking system	PV panel	E
[61]	León et al.	2014	México	Dual	Semi-passive	Dual	Solar concentrators	T
[62]	Ghosh and Haldar	2014	India	Dual	Active	Dual	Solar panel	E

(*continued on next page*)

Table 1 (*continued*)

Ref.	Authors	Year	Country & Location	Solar Tracking Method (Single or Dual)	Solar Tracking Mode (Active, Passive, Manual)	Solar Tracking Type	Tracking Application	Research (T, E, S, or A)[a]
[20]	Choi et al.	2014	Republic of Korea	Single	Manual, Active	Azimuth	Floating photovoltaic system	E
[63]	Le Roux et al.	2014	South Africa	Dual	Active	Azimuth-Elevation	Parabolic dish	S
[64]	Ferdaus et al.	2014	Bangladesh	Dual	Active	Azimuth and altitude	Photovoltaic system	E
[65]	Lwin and Win	2014	Myanmar	Dual	Active	Azimuth-Tilt	Parabola dish	E
[21]	Abadi et al.	2014	Indonesia	Single	Active	Horizontal	Photovoltaic panel	E
[66]	Sidek et al.	2014	Malaysia	Dual	Active, Chronological	Azimuth and altitude	Photovoltaic panel	E
[22]	Raza et al.	2014	Pakistan	Single	Active	Azimuth	Photovoltaic module to solar still	E
[110]	Peng et al.	2013	China		Active	New rotatable axis tracking system	Parabolic-trough collector for solar hybrid coal fired power plants	T
[67]	Li et al.	2013	Arizona, USA	Dual	Active	Horizontal, Vertical	Giant Fresnel lens solar stoves	T, E
[23]	Farooqui	2013	Pakistan	Single	Passive (gravity based)	Novel one dimensional tracking mechanism	Box type solar cookers	T, E
[24]	Sen et al.	2013	India	Single	Active	Horizontal	Fresnel mirror solar concentrator	T, E
[68]	Miloudi et al.	2013	Algeria	Dual	Active	Azimuth-Altitude	Photovoltaic Panel	T
[69]	Batayneh et al.	2013	Jordan	Dual	Active	Polar	PV system	T
[25]	Huang et al.	2013	Taipei, Taiwan	Single	Active	Azimuth	Solar PV system	E
[26]	Bawa and Patil	2013	Pune, India	Single	Active	Horizontal	Photovoltaic (PV) panel	E
[27]	Gama et al.	2013	Algeria	Single	Active	Horizontal	Parabolic trough concentrators (PTC)	E
[70]	Lee et al.	2013	Malaysia	Dual	Active	Azimuth and altitude	Photovoltaic system	E
[91]	Maia et al.	2013	Brazil	Single, Dual		Azimuth, Azimuth and altitude	Flat plate solar collectors	T
[28]	Mahendran et al.	2013	Malaysia	Single	Active	Horizontal	Photovoltaic Panel	
[29]	Peterson and Gray	2012	Queensland, Australia	Single	Passive		Solar powered desalination	E
[30]	Bhattacharya et al.	2012	Kolaghat, India	Single	Active	Polar	Solar module to connect wind energy (hybrid system)	E, S
[92]	Guihua Li et al.	2012	China	Single, Dual	Active	Vertical Single axis Tracking; Horizontal south-north axis and eat-west axis sun tracking, 2-axis sun-tracking	Solar panels	T
[93]	Mohammed and Karim	2012	Bangladesh	Single, Dual	Active	Tip-Tilt, Azimuth-Altitude	Photovoltaic array	E
[71]	Bortolini et al.	2012	Italy	Dual	Active	Azimuth-Altitude	A Fresnel lenses concentrating solar prototype	E
[31]	M. and Abdul Rahman	2012	Malaysia	Single	Chronological	Horizontal	Photovoltic Module	E
[72]	Bose et al.	2012	India	Dual	Active	Azimuth and altitude	Concave mirror	E
[73]	Lee et al.	2012	Korea	Dual	Active		Heliostat system	T
[74]	Cruz-Peragón et al.	2011	Spain	Dual	Active	Azimuth-Tilt	Photovoltaic system	T, E
[75]	Seme and Stumberger	2011	Slovenia	Dual	Active	Azimuth-Tilt	Photovoltaic system	T, E
[76]	Wei et al.	2011	China	Dual	Active		Heliostat to solar tower power plants	T
[94]	Tina and Gagliano	2011	Italy	Single, Dual	Active	Polar tracking, Azimuth-altitude	Hybrid solar/wind power system	T
[95]	Lubitz	2011	Canada	Single, Dual	Active	Azimuth tracking Two axis tracking	Solar panels	T
[96]	Koussa et al.	2011	Algeria	Single, Dual	Active	Vertical and inclined tracking	Photovoltaic systems	T, E
[77]	Abu-Malouh et al.	2011	Jordan	Dual	Active	Two axis tracking	Spherical solar cooker	E
[97]	Ma et al.	2011	China	Single, Dual		2-axis sun-tracking; vertical single-axis sun tracking	Solar panels	T, E
[32]	Chemisana et al.	2011	Spain	Single	Active		Solar cooling	S
[78]	Al-Soud et al.	2010	Jordan	Dual	Active	Two axis tracking	A parabolic solar cooker	E
[33]	Ferretti et al.	2010	Italy	Single	Active	Horizontal	Linear Fresnel Reflector Solar Plant	A
[79]	Robalo and Figueiredo	2010	Portugal	Dual	Active	Two axis tracking	PV	E
[80]	Kelly and Gibson	2009	USA	Dual	Active	Two axis tracking	Solar modules	E
[81]	Arbab et al.	2009	Iran	Dual	Active	Two axis tracking	Solar dish	E
[82]	Chong and Wong	2009	Malaysia	Dual	Active	Azimuth-elevation and tilt-roll tracking mechanism	Solar collector	T
[34]	Tanaka and Nakatake	2009	Japan	Single	Active	Azimuth tracking tilted-wick	Solar still	T
[35]	Tomson	2008	Estonia	Single	Active	North–South axis tracking	PV modules	T, E

(*continued on next page*)

Table 1 (*continued*)

Ref.	Authors	Year	Country & Location	Solar Tracking Method (Single or Dual)	Solar Tracking Mode (Active, Passive, Manual)	Solar Tracking Type	Tracking Application	Research (T, E, S, or A)[a]
[36]	Abdallah and Badran	2008	Jordan	Single	Active	Azimuth tracking	Solar still	E
[37]	Huang and Sun	2007	Taiwan	Single	Active	Horizontal tracking	PV	T
[38]	Mwithiga and Kigo	2006	Kenya	Single	Manual	Azimuth tracking	Solar dryer	E
[39]	Grass et al.	2004	Germany	Single	Active		Solar thermal collectors	T
[83]	Nuwayhid et al.	2001	Lebanon	Dual	Active	Azimuth – altitude tracking	Parabolic concentrator	E
[40]	Abouzeid	2001	Egypt	Single	Active		Solar cell panels	T
[41]	Michaelides et al.	1999	Cyprus, Greece	Single, Dual	Active	The single-axis tracking with variable azimuth, Seasonal tracking collector, Single-aixs tracking-axis parallel to the surface, Full Tracking	Thermosyphon solar water heaters	T
[98]	Abou-Ziyan	1998	Egypt	Single, Dual	Active	Azimuth - elevation tracking	The paraboloid dish solar cooker	T
[84]	Attalage and Reddy	1992	Thailand, USA	Dual	Active	Two axis tracking	Flat-plate solar collector	T
[99]	Gordon el al.	1991	USA	Single, Dual	Active	Polar-axis tracking and two-axis tracking	Photovoltaic systems	E
[85]	EL-Refaie	1989	Egypt	Dual	Active	Two axis tracking	Concentrator spherical reflector	E
[42]	Radajewski	1987	Australia	Single	Active	A single-axis tracking - a north-south axis	Photovoltaic arrays to water pumping	T, E
[43]	Salawu and Oduyemi	1987	Nigeria	Single	Active		Solar collector	T, E

[a] Evaluation way, Theoretical or Experimental or Simulation or Actual {(T) or (E) or (S) or (A)}.

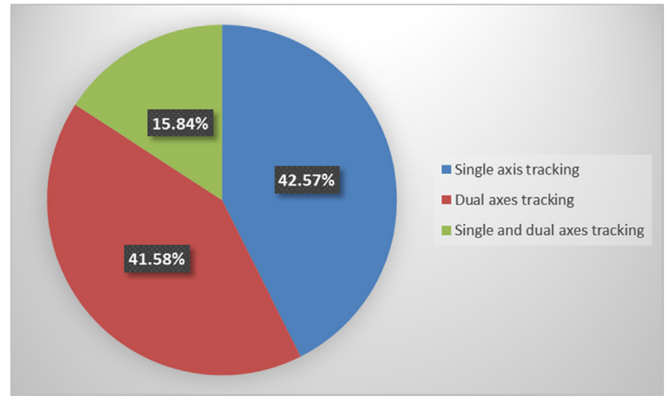


Fig. 4. Percentage of usage the solar tracking systems types in the recent studies.

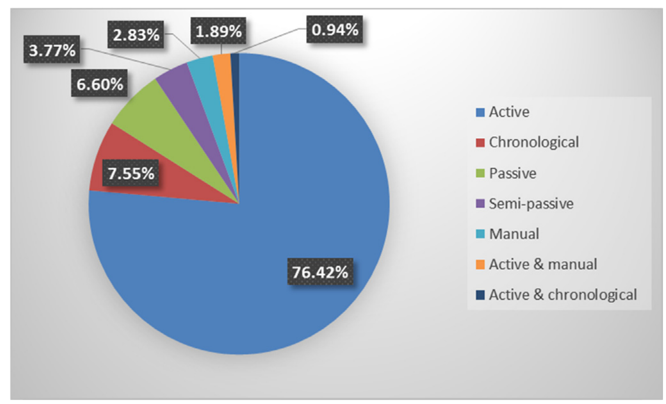


Fig. 5. Percentage of usage the solar tracker drive systems types in the recent studies.

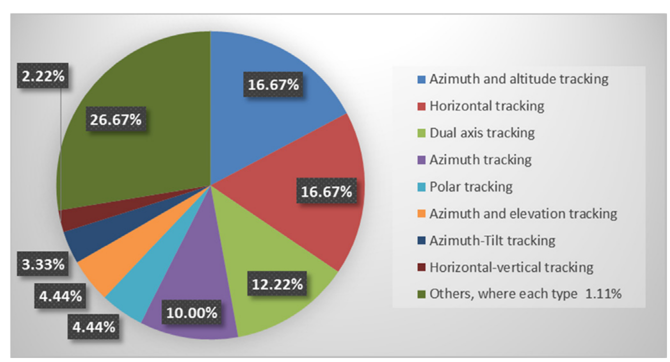


Fig. 6. Percentage of usage the solar tracking techniques in the recent studies.

4. Solar tracking systems

There are two main solar tracking systems types that depending on their movement degrees of freedoms are single axis solar tracking system and dual axis solar tracking system. In this section, we will discuss the recent studies of single axis tracking [1–43], dual axis tracking [44–85], single and dual axis tracking [86–100] with respect to the tracking systems types. The recent studies showed many special types under the main two types: a single-axis tracking - a north-south axis [42], azimuth tracking [7,11,13,16,20,22,25,36,38], horizontal tracking [2–6,8,12,21,24,26–28,31,33,37], polar tracking [15,17,30,69], vertical tracking [14], north–south axis tracking [35], dual axis tracking [44,45,61,62,77–81,84,85], azimuth and altitude tracking [48–51,54,55,58,60,64,66,68,70–72,83], azimuth and elevation tracking [56,59,63,98], azimuth-Tilt tracking [65,74,75], horizontal-vertical tracking [46,67], azimuth tracking, two axis tracking [95], azimuth, azimuth and altitude [91], azimuth tracking tilted-wick [34], azimuth-elevation and tilt-roll tracking mechanism [82], tip-tilt, azimuth-altitude [93], polar axis tracking, E-W tracking, N-S tracking [87], polar tracking, azimuth-altitude [94], polar-axis tracking and two-axis tracking [99], N–S horizontal tracking, E–W horizontal tracking, N–S tilted tracking [86], N–S tracking, fixed tilt concentrator [10], vertical and inclined tracking [96], VSAT, AADAT, azimuth-altitude [88], dual axis sun tracking; vertical single axis sun tracking [97], E-W axis with slope variable, N-S tracking with slope variable about tilt yearly [18], horizontal E-W axis, horizontal N-S axis, fixed slope rotated about a vertical axis, N-S axis - parallel to the Earth's axis, two axis tracking [89], vertical single axis tracking, horizontal south-north axis and eat-west axis sun tracking, 2-axis sun-tracking [92], inclined axis tracking system, vertical axis tracking system, dual axis tracking system [90], declination-clock mounting with two rotation axes: primary axis, located in E-W and secondary axis, perpendicular to the primary axis and able to rotate around it [57], the single-axis tracking with vertical axis, fixed slope and variable azimuth and the seasonal tracking mode where the collector slope is changed twice per year [41], bidirectional solar azimuth tracking with sliding axle [19], new rotatable axis tracking system [110], novel one dimensional tracking mechanism [23], and 2-DOF parallel robot (U-2PUS parallel robot) [100].

The predominant two categories of tracking – single and dual axis tracking – have different features compared to each other. Although the dual-axis tracking is more complicated and has a higher cost, which uses more instruments and equipment, compared to single-axis tracking, the statistics investigated through this study illustrates that the trend of the research for both types is approximately equal; 42.57% of studies focusing on single axis against 41.58% for dual one and the rest for investigating both. Certainly, the main advantage of using dual-axis tracking in comparison with single one is tracking the sun movement not only during the day, like in single-axis, but also taking into account the yearly movement, e.g. the altitude of sun from season to season. This advantage makes dual tracking more efficient and has higher solar energy gain when comparing against the single tracking system. Furthermore, for a simple comparison between both types in the context of applications, for example in concentrated solar power plants (CSP), most studies show a favorable trend of using dual-axis tracking in particularly solar dish and solar power systems whereas single-axis trackers are frequently used in parabolic trough collectors and linear Fresnel solar systems. By the following two subsections, in-depth discussion has been conducted for both types on the basis of the recent studies, which revolve around the two types.

4.1. Dual axis solar tracking system

A dual axis solar tracking system is a technique that tracks the sun in two different axes using two pivot points to rotate. Solar tracker system in this type usually has both horizontal and vertical axes. One of the most important applications to dual axis tracker are CSP applications and especially solar dish and solar tower systems where the long distance between the heliostat reflectors and the receiver point concentration lead to angle errors in the results. In active systems using dual axis tracking, we usually use four LDRs, two motors and a controller. The four LDRs are placed in different directions of rotation at the system, and each motor rotates the system in one axis when the controller detects the signal from the LDRs. Fathabadi [44] proposed a novel sensorless dual-axis solar tracking system with high accuracy controlled by the maximum power point tracking unit of photovoltaic systems. Fig. 7 shows both angles of the tracking systems; altitude angle is α, azimuth angle is α_w, altitude axis, azimuth axis, the horizon plane, and vertical plane [44]. Hong et al. [45] performed a preliminary study on the dual-axis direct and indirect tracking method to maximize the electricity generation of the smart photovoltaic blind. Fig. 8 shows the tracker types of the solar tracking systems, which consists of single axis

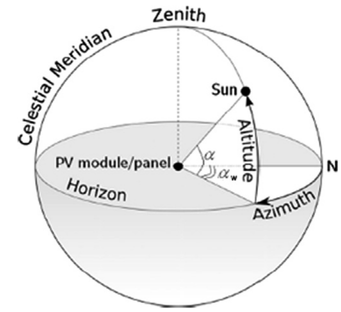


Fig. 7. Coordinate axes: altitude axis, azimuth axis, altitude angle, and azimuth angle [44].

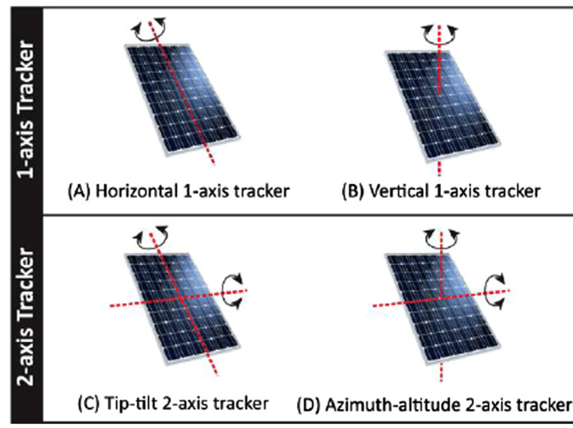


Fig. 8. Tracker types of Photovoltaic modules [45].

tracker and dual axis tracker. The single axis tracking tracks daily the sun from east to west and can be divided into horizontal single axis tracker and vertical single axis tracker in order to perform solar tracking centered on the horizontal and vertical axis of the PV panel, respectively. The dual axis tracking tracks the sun in both two directions, east-west motion and north-south motion, and can be divided to tip-tilt dual-axis tracker and azimuth-altitude tracker. The tip-tilt dual-axis tracker presents solar tracking centered both on the rotating axis of the SoP and the horizontal axis. The azimuth-altitude dual-axis tracker presents solar tracking centered both on the rotating axis of the SoP and the vertical axis [45].

Maia et al. [89] developed a mathematical model to predict the absorbed energy, useful energy gain and thermal efficiency of a flat-plate solar collector in Brazil. Moreover, several tracking systems were compared to fixed flat-plate solar collectors. The effect of the inlet water temperature, the number of covers, and the plate emittance was also investigated. Fig. 9 shows six types of tracking evaluated through a mathematical model to predict the absorbed energy, useful energy gain and thermal efficiency of a flat-plate solar collector in Brazil. The tracking modes demonstrated in the figure compared to fixed flat-plate solar collectors. The six types of tracking used in evaluation are as following: (R_1) The collector rotated over a horizontal east–west axis with continued adjustment to lower the incidence angle, (R_2) The collector rotated over a horizontal north–south axis with continued adjustment to lower the incidence angle, (R_3) The collector with a constant slope rotated along a vertical axis. The tilt angle was taken equally to the absolute value of the local latitude, (R_4) The collector rotated over a north–south axis, parallel to the Earth's axis with continued adjustment to lower the incidence angle, (R_5) The collector with continued tracking along dual axes to lower the incidence angle, (R_6) a fixed collector slope oriented to north, with 20̊ tilt angle [89].

Gholinejad et al. [87] studied the impacts of various tracking modes on the performance of a solar multi-effect distillation plant. Therefore,

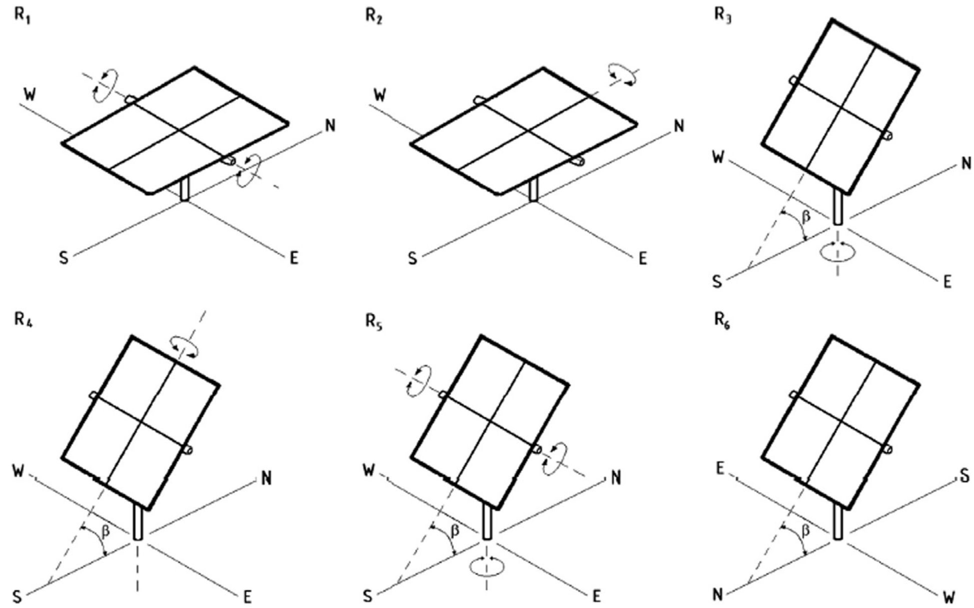


Fig. 9. Tracking types of flat plate solar collectors [89].

MATLAB code was developed and validated to experimental data to calculate amount of received radiation, useful energy, heat loss of parabolic collectors, and fresh water production of the desalination plant. Furthermore, the most appropriate tracking system for several altitudes was suggested with respect to the criterion of maximum fresh water production. In Fig. 10, Tracking systems for parabolic trough collectors were classified by means of motive modes: single-axis tracking mode rotated over east–west (E-W) or north–south (N-S) orientation or parallel to the earth axis and dual-axis mode through varying parabolic trough collector's position vertically and horizontally [87].

Panagopoulos et al. [88] proposed a policy iteration method (along with specialized variants), which is able to calculate near-optimal trajectories for effective and efficient day-ahead solar tracking. This was

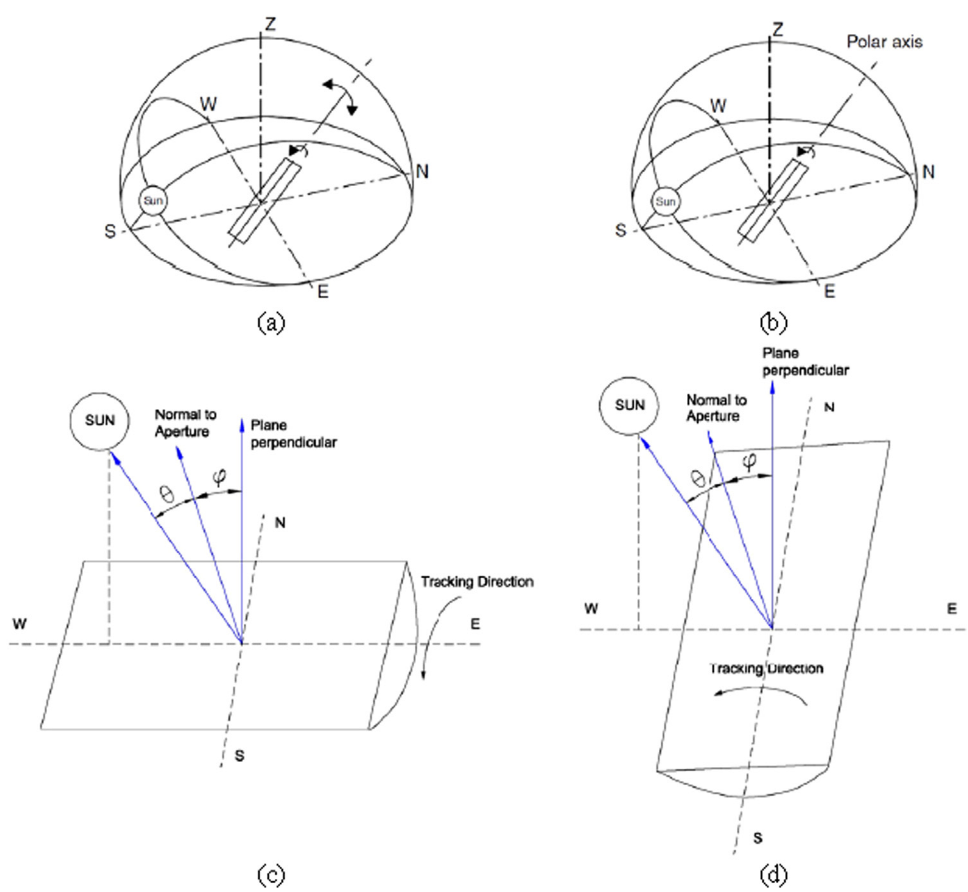


Fig. 10. Tracking modes for parabolic trough collector: (a) Full Tracking (b) Polar axis tracking (c) E-W tracking (d) N-S tracking [87].

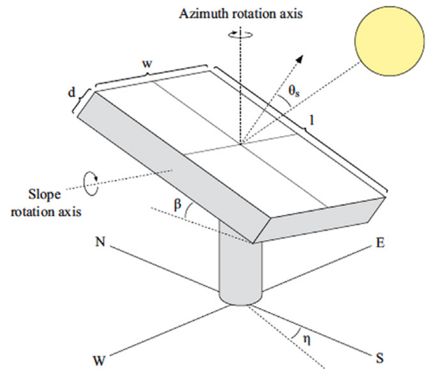


Fig. 11. AADAT (in VSAT is fixed) [88].

based on weather forecasts coming from online provider that increase the power output of a PVS considerably compared to standard solar tracking techniques. Fig. 11 illustrates AADAT tracking system with two degrees of freedom: an azimuth axis and elevation axis (rotating over a slope). VSAT rotates over azimuthal axis and slope angle is fixed [88].

Seme and Stumberger [75] proposed a novel method for determining the optimum trajectories of the sun tracking for a PV system with a dual-axis tracking. In addition, a new method to specify the direct and diffuse solar radiations on the surface of the PV panels, which is further confirmed by a comparison of the measured and estimated solar radiations for the clear days. Moreover, the inclusion of the tracking system consumption in the optimization procedure was considered. The proposed method was implemented in order to determine optimal trajectories of the azimuth and tilt angles where the energy is produced from the tracking PV system, which specified by measurements, was maximum considering a stochastic search algorithm named Differential Evolution as the optimization tool. Fig. 12 shows the dual-axis sun tracking mechanical structure system. The system is used PMDC 2 to change the tilt angle β to move in the direction North–South, while PMDC 1 to change the azimuth angle α_w to move in the direction East–West. The changes between two axes acted by switching on and off the PMDC motors supplied by 24 V batteries using the multi-stage gear ratio for the azimuth angle α_w are 12:40:52, and for the tilt angle β are 12:40:15 [75].

Chen et al. [55] showed the state space model of dish solar generation tracking servo system with the random disturbances of wind load and system parameter uncertainties. Fig. 13 shows one of the types of the solar thermal power generation using of parabolic reflector, dual-axis tracking system, receiver, thermoelectric converter, and power converter [55]

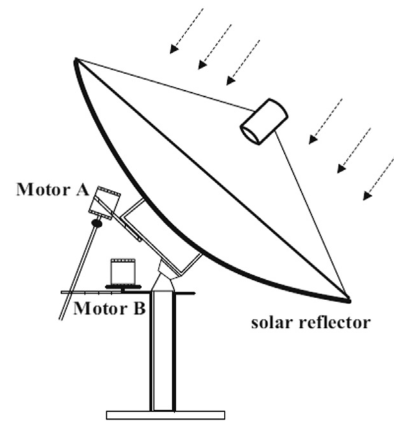


Fig. 13. Solar dish using dual axis tracking system [55].

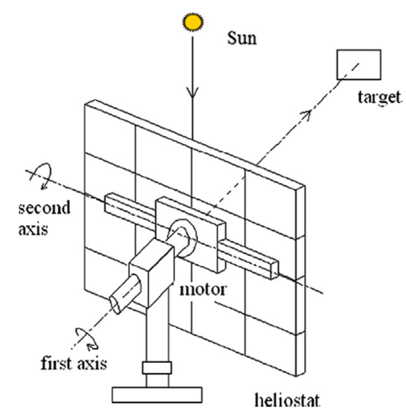


Fig. 14. The heliostat with target-aligned mount [76].

Wei et al. [76] derived a tracking and ray tracing equations for the target-aligned heliostat for solar tower power plants. With the equations, a new module for analysis of the target-aligned heliostat with an asymmetric surface integrated in the code HFLD. For validation the rightness of the derived equations, a target-aligned heliostat with a toroidal surface modeled, and the image of the target-aligned heliostat determined by the modified code HFLD and compared with that calculated by the commercial software Zemax. Fig. 14 shows the target-aligned heliostat, which has two rotation axes where the first axis fixed relative to the ground and points toward the target while the second axis perpendicular to the first axis and located in the heliostat plane. As

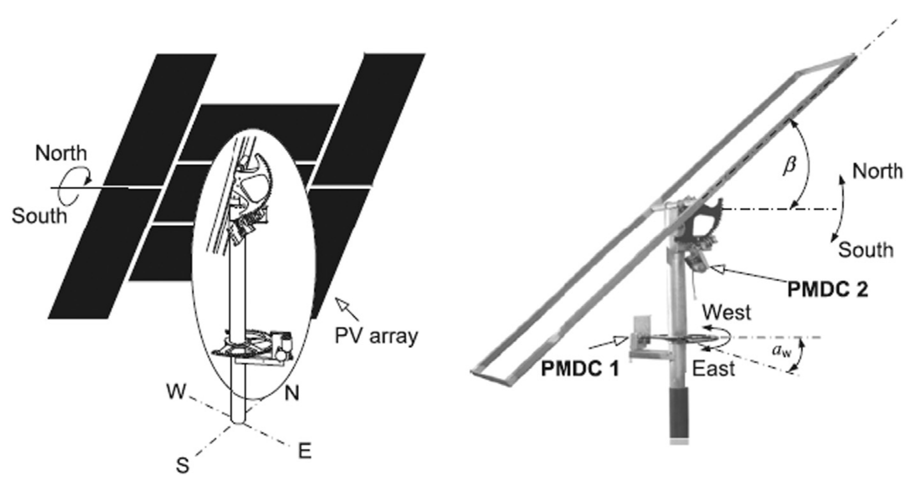


Fig. 12. Dual-axis sun tracking system with changing azimuth angle α_w and tilt angle β [75].

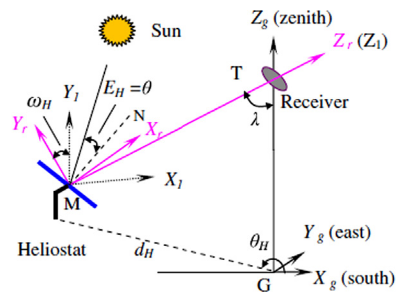


Fig. 15. Coordinate systems for deriving the rotation angle formulas for the target-aligned heliostat [76].

the sun path changes during the day, the heliostat rotates about the first axis firstly so that the incident plane of sunlight coincides with the meridian plane of the heliostat, and, then, the heliostat rotates about the second axis to reflect the sunlight to the target. The rotation angles of the heliostat can be calculated with (a) Solar time, (b) The heliostat locations on earth, and (c) The target locations on earth [76]. Fig. 15 presents Cartesian right-handed coordinate systems for deriving the rotation angle formulas to the target-aligned heliostat. The incidence and the reflection vectors pointing toward the sun from the heliostat location in ground-coordinates are illustrated in Fig. (16.a) and (b). Fig. (17.a) shows coordinate systems for deriving the ray tracing equations for the target-aligned heliostat. (b) Coordinate transformation are illustrated in Fig. (17.b) and (c) from heliostat coordinates to reflection-normal coordinates and from reflection auxiliary coordinates to target coordinates respectively [76].

Chong and Wong [82] described the general form of mathematical solution using coordinate transformation method to various types for sun tracking systems and for specific case studies as azimuth-elevation and tilt-roll tracking formulas. The sun's position vector relative to the earth-center frame defined as shown in Fig. (18.a), where CM, CE and CP represent three orthogonal axes from the center of earth pointing towards the meridian, east and Polaris, respectively. Fig. (18.b) shows the coordinate system in the earth-surface frame that consists of OZ, OE and ON axes, in which they point towards zenith, east and north respectively. The transformation of the vector S from earth-center frame to earth-surface frame obtained through a rotation angle that is equivalent to the latitude angle, ϕ. Fig. (19.a) presents new coordinate system that defined by three orthogonal coordinate axes in the collector center frame. In the collector-center frame, the origin O is defined at the center of the collector surface and it also coincides with the origin of earth surface frame. OV is defined as vertical axis in this coordinate system and it is also parallel with first rotational axis of the solar collector. Meanwhile, OR is named as reference axis and the third orthogonal axis, OH, is named as horizontal axis. The OR and OH axes form the level plane where the collector surface is driven relative to this plane. The simplest structure of solar collector that can be driven in two rotational axes: the first rotational axis that is parallel with OV and the second rotational axis that is known as EE' dotted line (it can rotate around the first axis during the sun tracking but must always remain perpendicular with the first axis). From the diagram, θ_r is the amount of rotational angle about EE' axis measured from OV axis, whereas β_r is the amount of rotational angle about OV axis measured from OR axis. Furthermore, α is solar altitude angle in the collector-center frame, which is expressed as $\pi/2-\theta_r$. In an ideal azimuth-elevation system as shown in Fig. (19.b), OV, OH and OR axes of the collector-center frame are parallel with OZ, OE and ON axes of the earth surface frame accordingly. Fig. (19.c) shows the combination of the three rotations in 3D view from collector center frame to the earth-surface frame, where the change of coordinate system for each axis follows the order: Z→V′→V, E →H′→ H and N→R′→R [82].

Many scholars attempted to develop innovative, cost-efficient techniques for dual-axis tracking type in order to maximize the quantity of solar energy captured from the sun, thereby enhance the overall gain and the electricity generated. However, the main challenge that encounters the researches in this particular type of tracking is the cost and complexity of the system compared to single-axis tracking; e.g. two

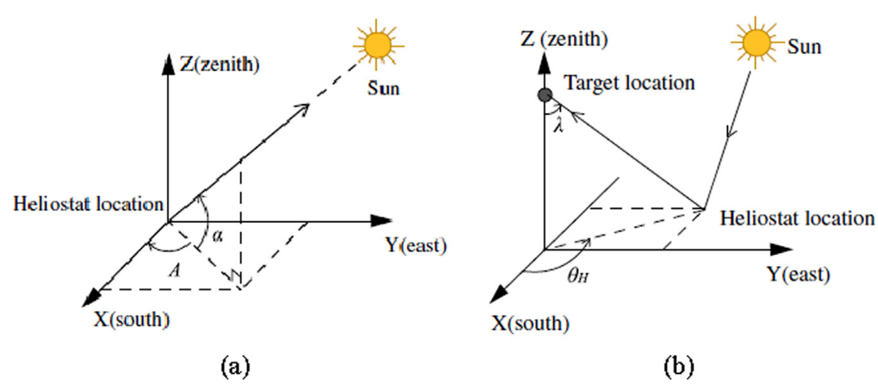


Fig. 16. (a) Incidence vector in ground-coordinates (b) Reflection vector in ground-coordinates [76].

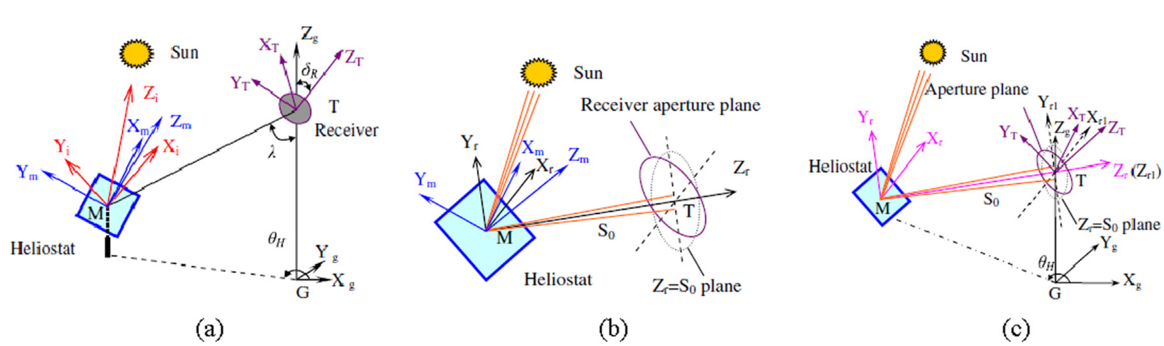


Fig. 17. (a) Coordinate systems for deriving the ray tracing equations for the target-aligned heliostat (b) Coordinate transformation from heliostat coordinates to reflection-normal coordinates (c) Coordinate transformation from reflection auxiliary coordinates to target coordinates [76].

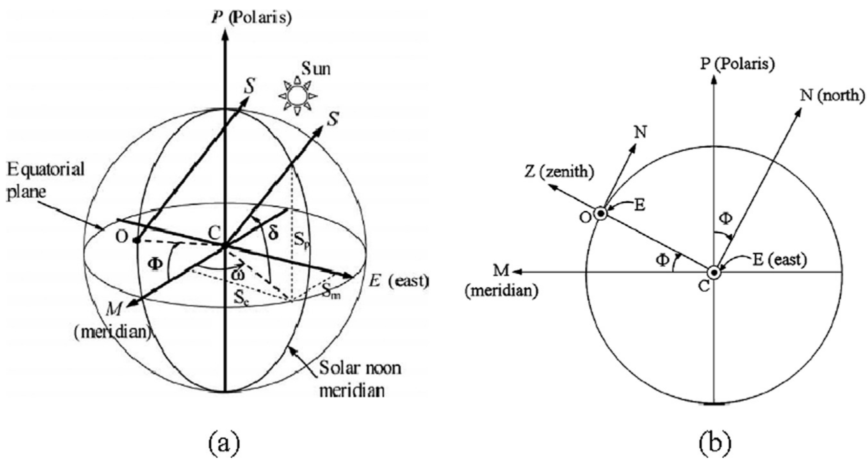


Fig. 18. (a) The sun's position vector relative to the earth-center frame. In the earth-center frame, CM, CE and CP represent three orthogonal axes from the center of the earth pointing towards meridian, east and Polaris, respectively (b) The coordinate system in the earth-surface frame that consists of OZ, OE and ON axes, in which they point towards zenith, east and north respectively. The transformation of the vector S from earth-center frame to earth-surface frame can be obtained through a rotation angle that is equivalent to the latitude angle, ϕ. [82].

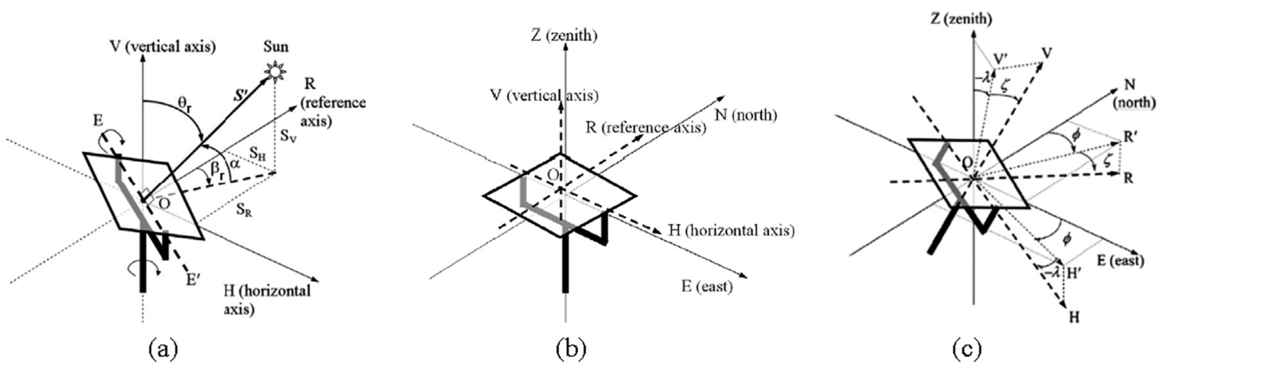


Fig. 19. (a) New coordinate system that defined by three orthogonal coordinate axes in the collector center frame. (b) In an ideal azimuth-elevation system, OV, OH and OR axes of the collector-center frame are parallel with OZ, OE and ON axes of the earth surface frame accordingly. (c) The combination of the three rotations in 3D view from collector center frame to the earth-surface frame, where the change of coordinate system for each axis follows the order: Z→V′→ V, E →H′→ H and N→ R′→R. [82].

motors are utilized for each axis with usually four sensors. Through the literature, some are directed their effort towards making double-axis tracking less complex such as developing accurate controller (maximum power point tracking) instead of using LDRs [44]; others, for instance, tries to ameliorate the electricity generated [45] or the heat/thermal energy gain [89]. The studies are conducted experimentally, e.g. on a simple PV systems, or theoretically, e.g. on a flat plate solar collector or parabolic collectors as a mathematical modeling. In terms of mathematical modeling and theoretical work, many studies are carried out in this area aiming to in-depth study dual-axis tracking in myriad applications: Matlab code, to enhancing efficiency of solar desalination [87]; mathematical model, estimating thermal energy in flat-plate solar collectors [89]; iteration and novel method, calculating optimum trakectories [75,88]; state space models, improving the performance of solar dish collector [55]; mathematical solutions, using coordinate transformation method [82]; deriving equations for ray tracing and tracking, implementing on target-aligned heliostat for solar tower power plants [76].

4.2. Single axis solar tracking system

A single axis solar tracking system is a technique to track the sun from one side to another using a single pivot point to rotate. This system has main three types: horizontal, vertical, and tilted single axis tracking system. The axis of rotation is horizontal with respect to the ground at the horizontal single axis tracking system, where the face of the system collector or module is oriented parallel to the axis or rotation, and this type usually used in tropical regions. The axis of rotation is vertical with respect to the ground at the vertical single axis tracking system, where the face of the system collector or module is oriented at an angle with respect to the axis of rotation, and this type usually used in high latitudes locations. The axis of rotation is between horizontal and vertical axes at the tilted single axis tracking system, where the face of the system collector or module is oriented parallel to the axis of rotation. The main CSP applications of the single axis tracker are parabolic trough and linear Fresnel solar systems. The main disadvantage of the single axis tracking system is that it can only track the sun during the daily movement and not the yearly movement, and, during the cloudy days, the efficiency of the tracking system is reduced by a large amount due to the rotation around only one-axis.

Wang et al. [6] designed automatic sun tracking system for parabolic trough solar concentrator using PLC and hydraulic drive and the tracking error of the system is less than 0.6°. Fig. (20.a) shows the rotation of a parabolic trough collector around the single axis tracking. The sunray vector S follows the tracking axis, ρ is the tracking angle, and i is the cosine of incidence angle. Fig. (20.b) shows u-r-b coordinate system, where r is the tracking axis, b is the axis that parallel to the earth surface and u is the third orthogonal axis [6]. Sallaberry et al. [9] presented a procedure for the estimation of the optical losses due to the positioning angle error of a single-axis solar tracker, used on a small-size parabolic trough collector. Fig. 21 shows the rotation angles defining the collector position for the testing procedure, in order to define the incidence angles of the solar radiation on the small-size parabolic trough collector. This procedure was presented for estimation of the optical losses due to the positioning angle error of a single-axis solar tracker [9].

Tanaka and Nakatake [34] determined the distillate productivity of one step azimuth tracking tilted-wick solar still with a vertical flat plate

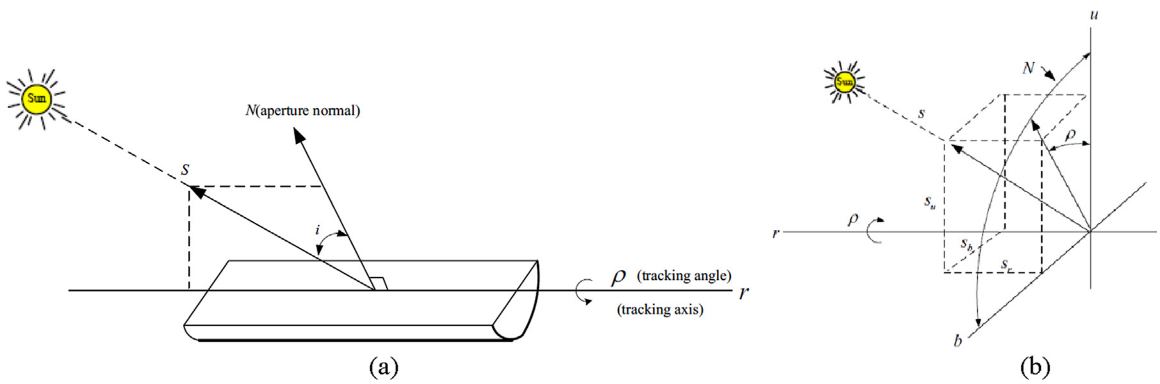


Fig. 20. (a) A single-axis tracking to solar parabolic trough (b) The u-r-b coordinate system [6].

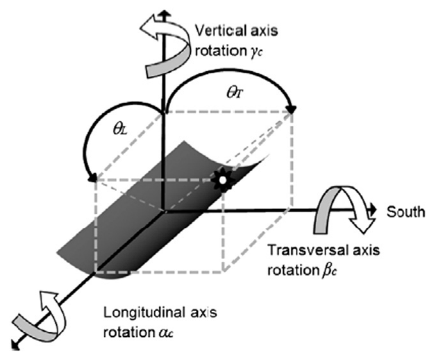


Fig. 21. Schematic diagram of the rotation angles: tracking angle α_c, collector inclination β_c, collector azimuth γ_c, the longitudinal and transversal angles θ_L and θ_T [9].

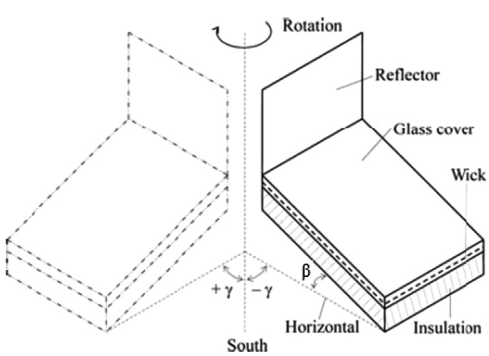


Fig. 22. Schematic diagram of one step azimuth tracking tilted-wick solar still with vertical flat plate reflector [34].

reflector at 30° N latitude during the four seasons: spring, autumn equinox, summer, and winter solstice. Fig. 22 shows azimuth tracking tilted-wick solar still system, which consists of an evaporating wick, a glass cover and a vertical flat plate reflector of highly reflective materials such as a mirror finished metal plate. The solar still tilted by the tilt angle, β, which vary every season and the orientation of the still, γ, which adjusted by manually tracking for ease of construction and maintenance of the still and the rotation just once a day at southing of the sun (near noon). During the morning the orientation of the still is southeast, but during the afternoon the orientation would be southwest [34]. Abdallah and Badran [36] showed a solar still with sun tracking system for enhancing the productivity by 22% compared to a fixed solar still and an increase of overall efficiency by 2%. Fig. (23.a) presents asymmetric greenhouse type still (ASGHT) shaped as an inclined box placed on a vertical tracking system which is one of the simplest types of solar stills with area of 1 m^2. The solar still consists of the frame from iron, the body from wood (16 mm) thick, a top cover of transparent glass, and the interior surface of its basin is blackened to enable absorption of solar energy to the maximum possible extent. In addition, the common fixed solar still is faced to the south. As shown in Fig. (23.b), single axis tracking used surface azimuth angle, α_w. The day is divided into four intervals where the vertical sun tracking motor is used for the joint rotating around the vertical axis to control α_w [36].

Michaelides et al. [41] simulated a thermosyphon solar water heater using the TRNSYS with three different solar collector-tracking modes in Nicosia-Cyprus and Athens-Greece, and it is shown that the best results from the thermal performance is single axis tracking system. The fixed tilted thermosyphon solar water heater, which consists of two flat plate solar collectors with total surface area 3 m^2, tilted 40°, and a storage tank with the capacity 162 liters. Fig. (24.a) shows the mode of single-axis tracking-fixed slope variable azimuth, and the actual setup shown in Fig. (24.c) where there are additional costs in this design in

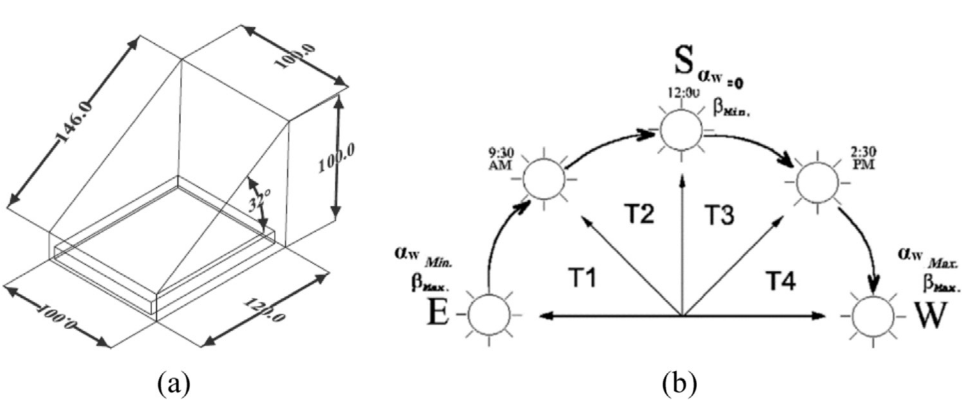


Fig. 23. (a) Schematic diagram of the single slope solar still (dimensions are in cm) (b) The division of daylight time into four intervals [36].

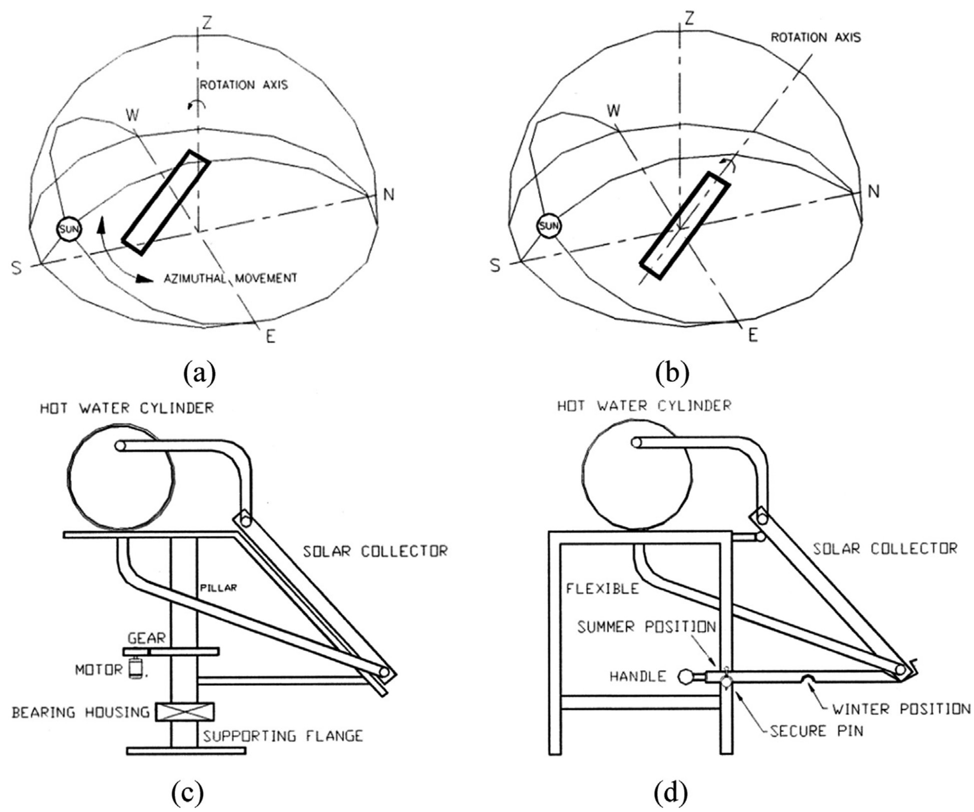


Fig. 24. (a) Single-axis tracking-fixed slope variable azimuth (b) Single-axis tracking-axis parallel to the surface (c) Practical solution of single axis tracking-fixed slope variable azimuth (d) Seasonal tracking collector [41].

comparison with the conventional fixed solar collector. This additional cost is due to the motor, the special framework with a bearing, and the tracking controller added to the tracking system. Fig. (24.b) shows the mode of single-axis tracking-axis parallel to the surface where the collector rotated in an E-W direction. In Fig. (24.d), the actual setup of the seasonal tracking, where there are additional costs in the design as compared to the conventional fixed solar collector due to the fixture with handle for manual slope adjustment added to the tracking system [41].

Zhong et al. [127] investigated sun-tracking technique, ISNA-3P sun-tracking attitude angle of solar panels is daily adjusted three times at three fixed positions: eastward, southward, and westward in the morning, noon, and afternoon, respectively, where solar panels rotates about the inclined south north axis. Fig. (25.a) and (b) shows the solar panel where the tracking axis is oriented in south-north direction and inclined at a tilt-angle from the horizon, β_{SN}. Solar panels are oriented eastward, ϕ_a from the solar-noon position in the early morning, and, then, solar hour angle $-\omega_a$ and solar panels are turned towards south and rotating about the ISNA, then adjusted once again [127]. Ma et al. [97] described a mathematical method and monthly horizontal radiation to investigate the optical performance of solar panels sun tracking system where it is adjusted three times at three fixed positions: eastward, southward and westward in the morning, noon, and afternoon, respectively, and solar panels rotating about the vertical axis three azimuth angles. Fig. (25.c) and (d) show the solar panel where the azimuth angle changed three times per day by rotating it about the vertical axis and the tilt angle of the solar panel from the horizon, β_{3A}. Solar panels are oriented eastward, ϕ_a from due south in the early morning, then solar hour angle $-\omega_a$ and solar panels turned towards due south, but solar hour angle ω_a, solar panels adjusted again westward, ϕ_a from due south [97].

Li et al. [92] investigated the optical performance of the vertical single-axis tracked solar panels compared to fixed and full 2-axis tracked solar panels using a mathematical procedure to estimate the annual collectible radiation. Fig. (26.a) shows the coordinate system of the PV vertical single-axis tracker where the X-axis normal to the horizon and pointing to the top of sky dome, Y-axis pointing to east and Z-axis pointing to due north, incidence angle of solar rays on the tracked panel, θ_1, and β_1 is the tilt-angle of v-axis tracked solar panels with respect to the horizon [92]. Li et al. [128] investigated the optical performance of the inclined south-north single-axis tracked solar panels using a mathematical procedure to estimate the annual collectible radiation. Fig. (26.b) shows the coordinate system ISN-axis used: X-axis pointing the southern sky dome, Y-axis pointing due east, Z-axis parallel to ISN-axis, the incidence angle of solar rays on the ISN-axis tracked panel, θ_1, and the tilt-angle of the tracked panel relative to the horizon, β_1 [128].

Tomson [35] described the performance of PV modules with daily two-positional tracking around the north–south axis; one in the morning and the other one in the afternoon. It is found that the seasonal energy increased by 10–20% over from a fixed south-facing collector tilted at an optimal angle. In the northern hemisphere, the best performance of fixed FPCs, while facing south with the zero azimuth $\gamma_0 = 0$, and at the latitude of 60° N, A tilt angle of $\beta_0 = 45°$ used as shown in Fig. (27.a). The collector is rotated twice per day with the deflection angles +X to -X where the two positions with the new tilt angle β_X and two new collector azimuth angles + -γ_X to -γ_X as shown in Fig. (27.b) [35]. Huang and Sun [37] designed one axis three position tracking PV module at three fixed angles: morning, noon and afternoon, and each PV module have own sun tracking frame and found power generation increased by 24.5% compared to a fixed PV module for latitudes less than 50°. A single axis tracking system with three positions mechanism are shown where the system consists of a PV frame driven by a motor, a single pole support, a solar position sensor, and a tilt adjustable platform to present the tilt angle of the solar tracker. The transmission gear of the PV frame has three touch switches mounted on it for signal

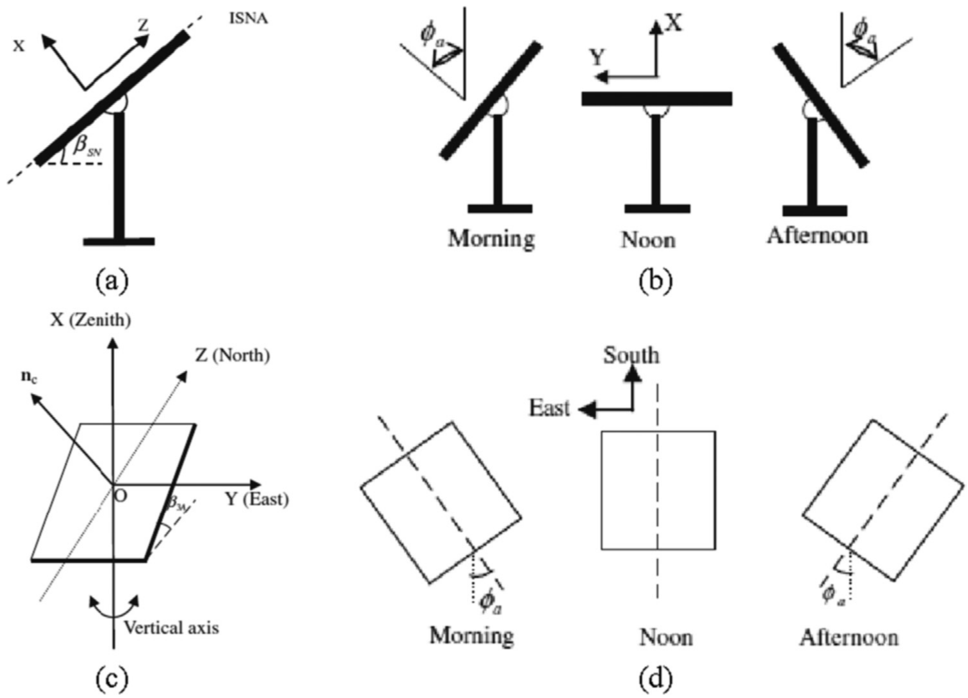


Fig. 25. (a) Side view of ISNA-3P tracked solar panels at solar-noon position [127] (b) Three attitudes of ISNA-3P tracked solar panels (Back view in the direction of the ISNA) [127] (c) Geometry of three azimuth angles tracked solar panels [97] (d) Three orientations of 3A tracked solar panels (top view) [97].

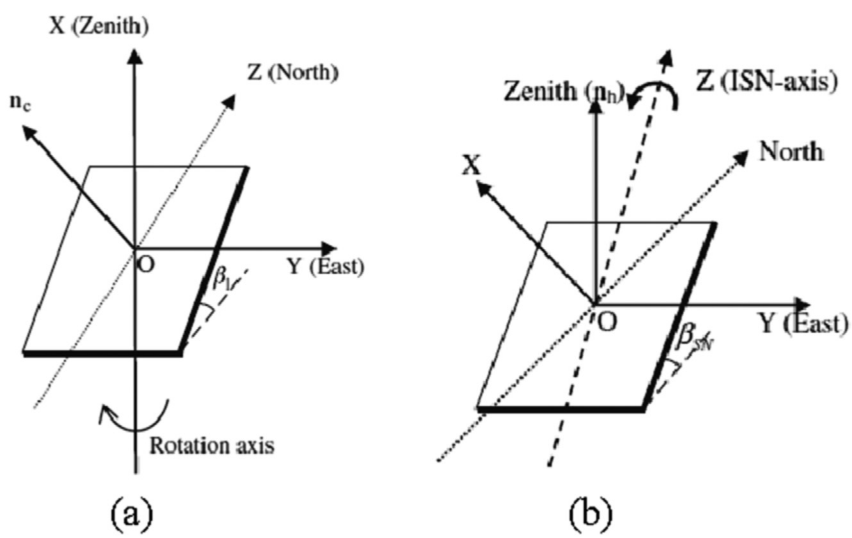


Fig. 26. (a) Geometry of v-axis tracked solar panels [92] (b) Coordinate system, ISN-axis [128].

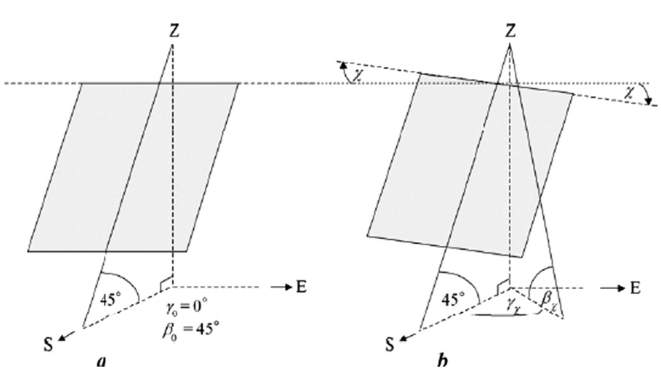


Fig. 27. Discrete tracking of a tilted solar collector [35].

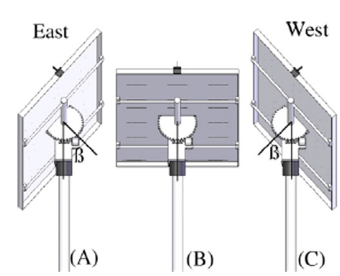


Fig. 28. Concept of one axis three position tracking [37].

outputting to the control circuit to determine the stopping angle where the PV module facing toward south at solar noon and the three positions for morning (A), noon (B) and after- noon (C) as shown in Fig. 28. Fig. 29 shows the coordinate system of the one axis three position

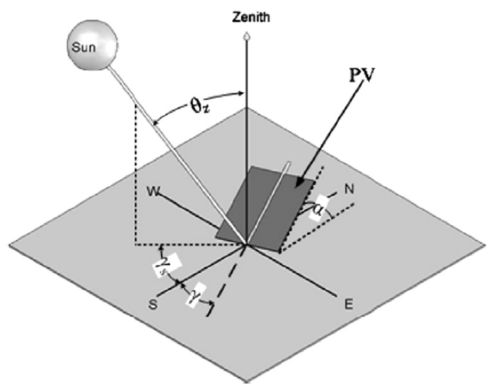


Fig. 29. Geometric definition of the PV module [37].

tracking PV module to calculate the instantaneous solar radiation incident. The stopping angle, β_s, is the solar incident angle related to the PV normal vector θ, solar declination angle δ, and the zenith angle θ_z with respect to the PV tilt angle β [37].

Sen et al. [24] fabricated and deigned a linear Fresnel mirror solar concentrator (LFMSC) with a mechanical tracking device for small scale applications, specifically raising steam. The system utilized long thin strips of mirrors to focus sunlight on to a fixed receiver located at a common focal line. Fig. 30 shows a schematic diagram of linear Fresnel concentrator reflectors, which consists of flat mirrors mounted on tubes placed on flat plate base and these mirrors, reflects the sunrays to the target line. In addition to achieve the high concentration factor, there are three parameters to each individual mirror are the clearance, tilt and width [24].

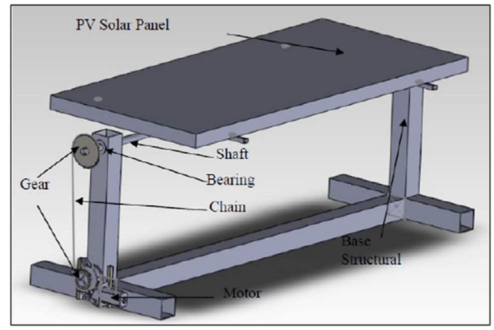


Fig. 32. CAD drawing of Single-axis tracking PV [28].

Mahendran et al. [28] compared the power output and efficiency of single-axis tracking solar panel with fixed solar panel experimentally in East Coast Malaysia. Fig. 31 showed the schematic diagram of the two systems and the pyranometer to solar radiation measurements, and actual prototypes with LDR and PIC microcontroller system. The CAD drawing of the single axis tracking system is shown in Fig. 32.

From the previous review for single axis tracking, the main features of this type of tracking compared to the dual one is the simplicity – lower cost and energy consumptions for the system itself – using usually one motor tracking the sun from only one side whether horizontally, vertically or over the tilted angle. However, for the single axis tracking, it shows lower efficiency and energy gain, for the same conditions, against two-axis tracking. Many studies carried out to investigate single-axis tracking system in lots of different applications aiming to

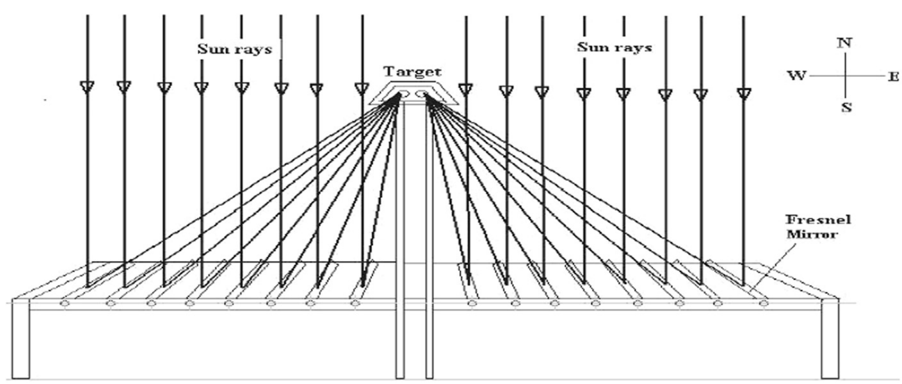


Fig. 30. Schematic diagram showing sun rays reflected to the receiver by the reflector [24].

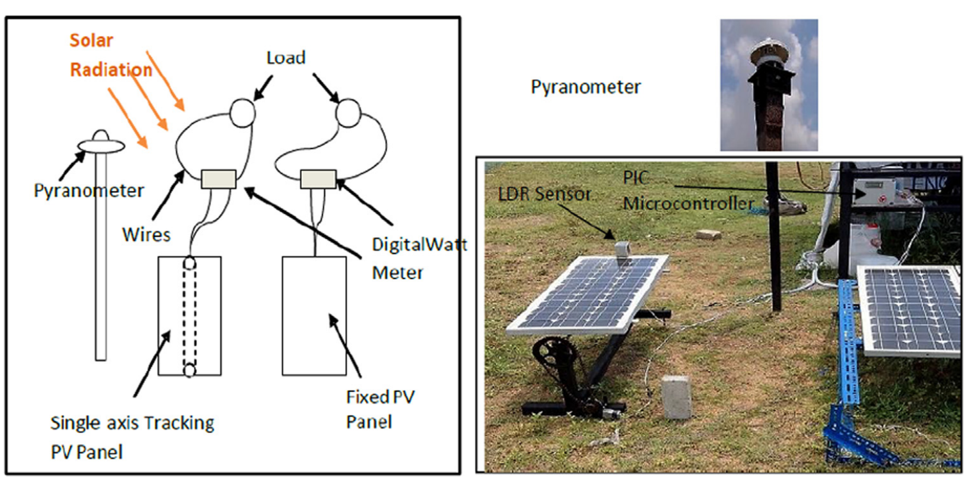


Fig. 31. Schematic diagram and actual photograph of PV Solar Panels [28].

improve further its efficiency. Some scholars focus their research in making comparisons between single-axis tracking and the fixed one [28,36,37,41,92] delineating the advantage of using tracking in terms of overall efficiency and solar energy gain. Others shade the light on the overall system performance in many applications: parabolic trough collectors, e.g. either by calculating the positioning angle error of tracking [9] or by using PLC and hydraulic drive [6]; solar desalination, by measuring the productivity for solar still [34,36]; PV panels and modules, through estimating its performance against different positions of tracking [28,35,37,97,127]; heating applications, within simulating a thermosiphon solar water heater [41]; solar concentrator, by designing and fabricating linear Fresnel mirror [24]. Moreover, mathematical methods/procedures were conducted to quantify the optical performance whether for making comparison between a specific type of single-axis tacking and fixed and dual ones [92] or by being adjusted at different fixed positions [97,127].

5. Solar tracker drive types

The solar tracker drive systems are classified to five types based on their tracking technologies: active tracking, passive tracking, semi-passive tracking, manual tracking, and chronological tracking. In this section, we will discuss the recent studies of active [1,3–13,15,16,18,19,21,22,24–28,30,32–37,39–56,58–60,62–65, 67–90,92–96,98–100,108–110], chronological [2,31], manual [38], active (normal tracking), manual (daily adjustment on primary axis) [57], active, manual [20], active, chronological [66], passive [14,17,23,29,111], semi-passive [61,112] with respect to the tracking technologies types.

The five main types of tracker drivers have plenty of advantages, disadvantages, features, components used, and even in the operating principles. The active solar tracker drive system is considered as the most widely used and investigated among the scholars compared to the other four types. Studying this type is particularly considered for enhancing the performance and accuracy of solar tracking dealing with mainly control circuits and signals from sensors to measure the amount of light. Likewise, the chronological tracking type which uses control system but with different operating principle; it depends on the chronological data collected to define the accurate tracking position, which is more energy-efficient since there is no losses of energy due to calibration. On the other hand, for passive, semi-passive and manual tracker devices, the aims of studying these types is mainly directed to the simplicity and lower the movements – in other words, the components used – resulting in lower cost and easy to deal with in terms of operation. Each type of tracker drivers will be in-depth studied and investigated by mentioning and focusing the recent literature, throughout the following subsections.

5.1. Active tracker

Active solar tracking system is the system that determines the position of the sun path in the sky during the day with the sensors. These sensors trigger the motor or actuator to move the drive system to the system towards the sun throughout the day. If the solar radiation beams are not perpendicular on the solar tracking system, then this will made a difference in light intensity on one sensor as compared to another leading and this will act the tracking system to be perpendicular on the sunlight beams. The first active tracking systems showed in 1975, the system presented by McFee, which is an algorithm that used to calculate the total power in a central receiver of a solar power system and to determine the distribution of flux density in it. The error tolerance of the position of the sun was between 0.5° to 1°. Active tracking system sorted with different control types as microprocessor-based, electric-optical sensor-based, date and time methods, and auxiliary PV cells [64,113].

Active tracking systems using microprocessor and electric-optical sensors are used at least two photoresistors or PV cells. A comparison between the output signals of the two variables parameters is conducted, and, subsequently, send signal of the difference between them to the drive motor. In solar tracking systems with auxiliary bifacial solar cells, the cells trigger the drive system to move to the desired position. In solar tracking systems that depend on the date and time, mathematical algorithm is calculated by the computer and then generated control signals of the system. At cloudy days, this system is not accurate where the sensors cannot made a decision due to the low solar irradiance intensity difference between the sensors [64].

Concerning the main two types of active tracking systems (the auxiliary bifacial solar cell based and microprocessor and electric-optical sensors based), some lucid features is existed between the types. As such, microprocessor and electric-optical sensors based is widely used and frequently studied and investigated by scholars in comparison with auxiliary bifacial solar cell based type; however, both are widespread in PV applications compared to the other solar systems applications that use tracking systems. The two types are quiet similar in sending signals to trigger/actuate motors to the right tracking position based on the measurements coming from the mounted sensors whether photoresistors, in microprocessor and electric-optical sensors based type, or solar cells, in auxiliary bifacial solar cell based type. Likewise, both types share the same disadvantage that they do not perform efficiently during cloudy days, as mentioned before, because both depend on light sensors which will be deficient in this case.

5.1.1. Microprocessor and electric-optical sensor

Microprocessor and electric-optical sensors are the most important type of active tracking control systems based on the closed loop circuits, which depend on the principles of control through feedback. In this principle, the inputs derived from sensors detect relevant parameters and then send them to the controller. Then, the parameters are analysed by the controller, which governs the output. Solar power arrays play an important role in the design of the solar tracking systems with high precision designed systems. In addition, due to the large scale and widely use of PV systems for different applications, this type of solar tracking systems are widely used [114]. This type usually consists of at least one pair of anti-parallel connected PV solar cells or photo-resistors. In case of equal intensity of illumination by both sensors, it will be balanced so that there is negligible control signal to a driving motor.

Zogbi and Laplaze [115] constructed dual-axis tracking system with two angles (azimuth and elevation) in 1984 using four electric-optical sensors, which placed in four quadrant formed using two rectangular plans with cross one another in a line. In order to compare the signals received from the sensors in each pair, an amplifier and other electronics components in the tracking control circuit are used. Then operates the two tracking motors using the signal received, and, at the beginning of the night, the system reset to its initial position. The motor is operated by an amplifier when the output of one of the sensors is greater than the threshold set. Rumala [116] presented a close loop control tracking system depending on the shadow method in 1986. Four photoresistors sensors are placed on a rigid platform, which has two articulated arms powered by engine's camshaft. The photoresistors are under a pair of cylinders mounted back to back East-West (E-W) and North-South (N-S). The control circuit is a signal conditioning circuit using a low pass filter, which feed an amplifier. It sends the signals to drive a servomotor for tracking and aligning the system through the difference of detected solar radiation, and, during the night, the system remains at the same position until sunset then autostart in the morning.

Kalogirou [117] presented a single-axis tracking system using three light dependent resistors (LDR) for the first time in 1996. The first LDR detects the focus state of the collector while the second and third LDRs discriminate the information between day and night and detects the presence or absence for shadowing. An electronic circuit received the signals from the output of the three LDR that triggers a low speed 12V/DC motor. Fig. (1.a) shows electro-optical sensors control signal where

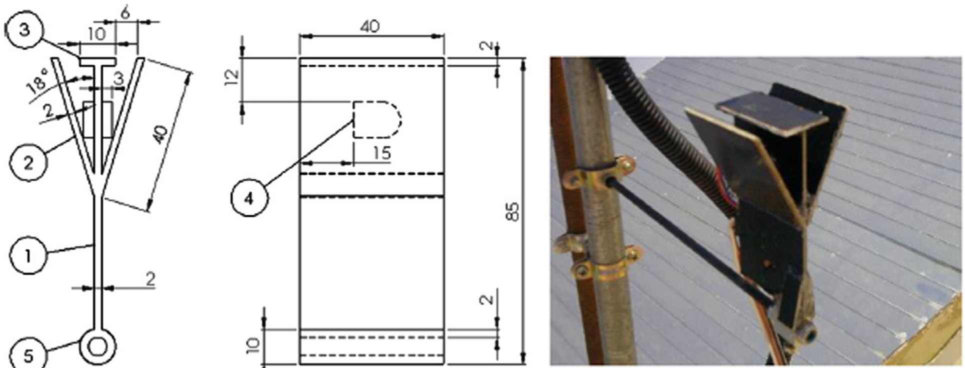


Fig. 33. The new sun-pointing sensor detector [27].

differential signal occurs to drive a motor by differential illumination until the illumination become equal between the two sensors. To increase the photocurrent sensitivity, the photo-resistors added on tilted surfaces as shown in Fig. (1.b). Fig. (1.c) shows a collimating tube to prevent diffuse radiation, which used as the shading device to PV applications [114]. Khalifa and Al-Mutawalli [118] showed dual-axis solar tracking system on a parabolic concentrator to improve the thermal of it where the tracking system is designed to track the sun every 3 min with respect to horizontal plane and 4 min with respect to the vertical plane. Abu Khader et al. [129] showed practical two axis solar tracking at Jordan using PLC solar tracker system, where the two drivers are around the vertical axis, and another one around the N–S or E–W axes. The overall increase is about 30–45% compared to the fixed PV system and estimation of power consumed by electrical motor and control circuit is about less than 3%.

Parthipan et al. [47] developed an automatic one axis three position solar tracking system with both degrees of freedom which sense the sunlight using sensors, Light Dependent Resistor (LDR). The system was designed to minimize the complexity and lower the cost and the same was tested. Gama et al. [27] proposed a new single axis sun tracking system based on absorber displacement, and investigated on a movable adjustable absorber for parabolic trough concentrators (PTC). As shown in Fig. 33, the sun position sensor consists of (1) a main vertical plastic plate, (2) two angled side plastic plates to eliminate the diffused solar radiation, (3) a small horizontal plastic plate to provide shade on the two LDR, (4) light dependent resistor (LDR) on each side. The orientation of the PTC to rotate on the sun direction using a voltage divider circuit, whose each part contains LDR and a protective resistor, are shown in Fig. (34.a) and (b) [27].

Das et al. [56] presented the design of a smart dual-axis solar tracker and developed it using microcontroller ATMEGA-8 L. Fig. (35.a) shows a schematic diagram of smart dual-axis tracker using four LDR sensors. Fig. (35.b) shows an incidence angle (θ_i) which is the angle between the incident sunlight and the perpendicular to the PV panel. Fig. (36.a) and (b) shows the practical system frontside and backside of six PV panels which is connected in series using two axis tracking system at the National Institute of Solar Energy (NISE), India [56].

Ghosh and Haldar [62] developed a solar tracker using AT89C51 microcontroller and LDR to control the movement of the solar panel. Ferdaus et al. [64] presented the design, implementation, and testing of a hybrid dual axis solar tracking system and compared the performance with both the static and continuous dual axis solar tracking system.

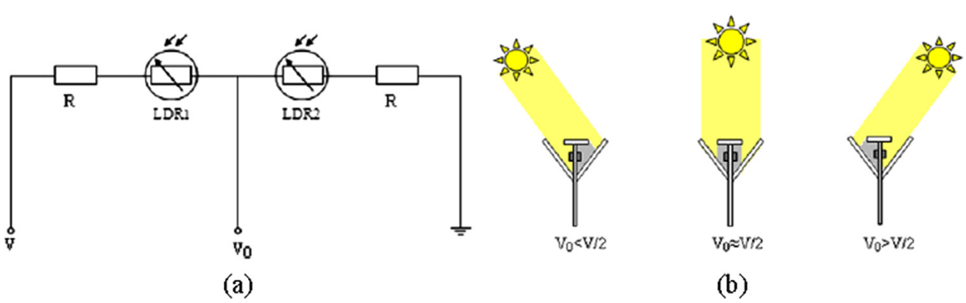


Fig. 34. (a) Electronic schematic of sun-pointing sensor detector (b) Different sun positions regarding the sun-pointing sensor detector [27].

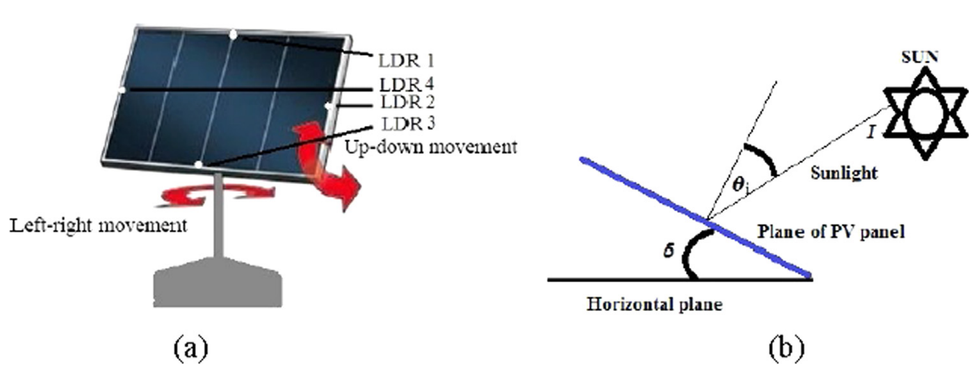


Fig. 35. (a) Schematic diagram of smart dual-axis tracker (b) Angle of sunlight to the plane of photovoltaic panel [56].

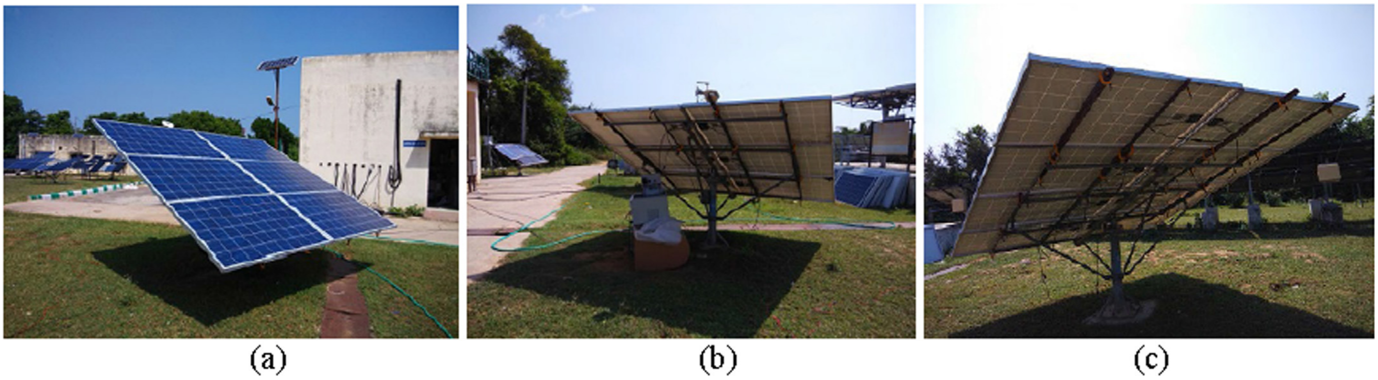


Fig. 36. Experimental setup with (a) Frontside of smart tracking system (b) Backside of smart tracking system (c) Backside of fixed photovoltaic panel system [56].

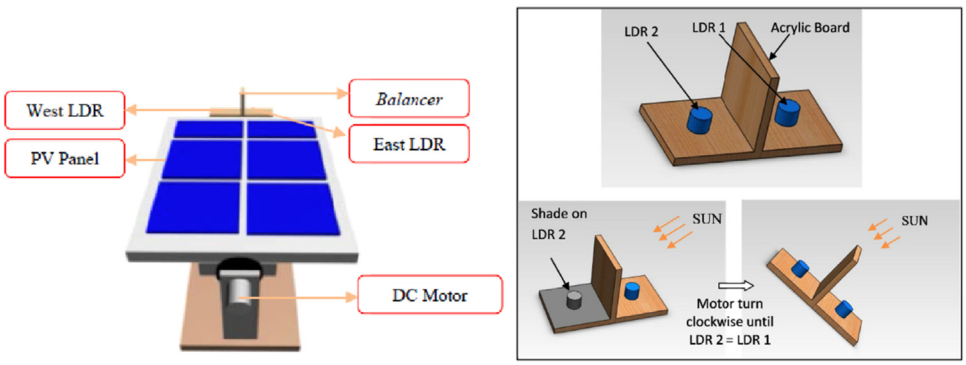


Fig. 37. (a) PV panel perspective diagram [21] (b) Tracking system working principle using LDR [28].

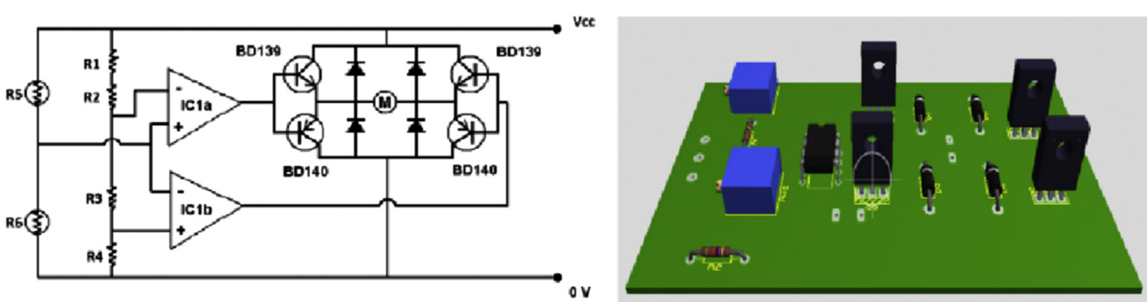


Fig. 38. Electrical circuit, the two amplifiers IC1a and IC1b are in an integrated circuit LM1458 (National Semiconductor) [59].

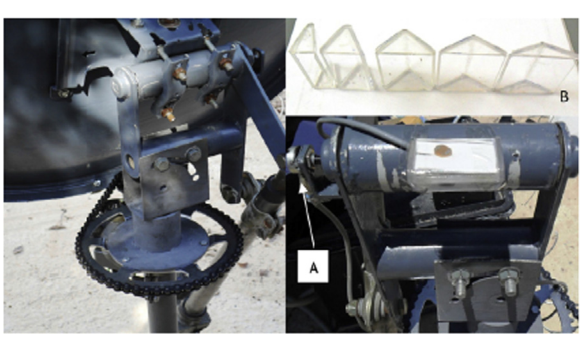


Fig. 39. Experimental system (A) angular sensor, (B) pyramidal supports of sensors [59].

Abadi et al. [21] proposed and executed a fuzzy logic controller for a solar tracking system (one input – one output) and implemented on ATMEGA 8353 microcontroller to increase power gain of PV panels which it exceeded 47% compared to the fixed panel. Fig. (37.a) shows

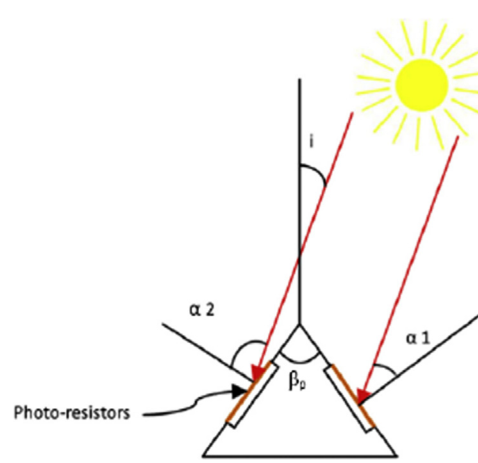


Fig. 40. Sensor geometry along with incidence angles [59].

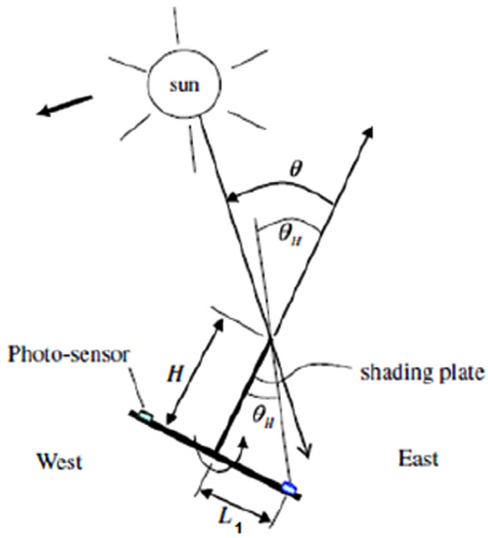


Fig. 41. Schematic of sun position sensor [37].

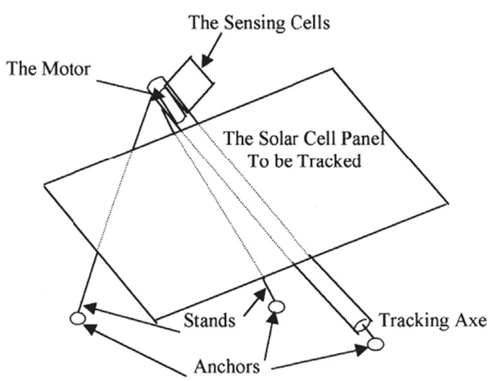


Fig. 42. The tracking system using two opposite position sensors [40].

PV with two LDR sensors to control the tracking system to sense the position of the sun in vertical axis [21]. LDRs are showed with their positions and the principle of working in Fig. (37.b) [28].

Bentaher et al. [59] constructed and tested a simple tracking system based on light dependent resistors (LDR's). The accuracy of the system was determined with respect to the angle between the two LDR, and the optimal angle between photo-resistors estimated numerically and experimentally. A simple tracking system designed and tested based on light dependent resistors (LDR's). Fig. 38 shows the electric circuit which is based on the comparison between LDR's resistivity. It is considered a gain of unity for both amplifiers. In order to investigate the difference of the light dependent resistors against its direction towards the sun, a mechanism of photovoltaic and/or parabolic concentrator with dual-axis orientation considered. Two DC motors (12 V) are used to actuate and move the two axes in addition to control the movement of the two axes by the two angular sensors, as shown in Fig. 39. For changing and dusting the direction of the sensor tracked the sun, an angular rotation was used besides maintaining the articulation axis horizontally. Moreover, a pyramidal sensor is used as shown in Fig. 40, which illustrates the geometric form of the sensors. The influence of Beta angle (β_p) investigated on the accuracy of various pyramidal sensors (30°, 60°, 90°, 120° and 140°). The two light dependent resistors resistivity is measured by a digital multimeter in each angular position case [59]. Huang and Sun [37] designed one axis three position tracking PV module at three fixed angles: morning, noon and afternoon and each PV module have own sun tracking frame and found that the power generation increased by 24.5% compared to a fixed PV module for latitudes less than 50°. Fig. 41 illustrates the solar position sensor design, which determines the switching time to transfer the PV to the next position, where L_1 is the distance of the photosensing element from the plate, and H is the height of the shading plate. An analog control circuit intends to move to the next position when the sensor signal triggered on the frame.

As mentioned, Microprocessor and electric-optical sensors is the most widely used not only in active tracking but also in all tracker types in general. It is also shown that this type is also widespread in Photovoltaics applications [21,37,47,56,59,62,64,114–117,129] and few studies in applications related to parabolic concentrators [27,118]. Some scholars directed their interest to study this type by implementing it on dual-axis tracking systems using two electric motors as actuators [56,59,64,115,116,118,129] while others focused on investigating one-axis tracking using microprocessor and electric-optical sensors to actuate only on DC motor [21,27,37,47,117]. Regarding the number of the light dependent resistor (LDR) used, there is a discrepancy among the literature but it is mostly limited to two electric-optical/photo-resistors sensors [21,37,59], using mostly in single axis tracking; three sensors [117], which is rare and widely used in single axis tracking; and four ones, frequently utilized in dual-axis tracking systems [56,115,116]. Furthermore, some researchers studied this type of tracking drivers using different types of controllers: ATMEGA-8 L microcontroller [56], AT89C51 microcontroller [62], fuzzy logic controller (ATMEGA 8353 microcontroller) [21], and PLC solar tracker system [129].

5.1.2. Auxiliary bifacial solar cell based

This system is one of active tracking system types. The bifacial solar cell senses and, then, drives the motors to the correct position of system, where the driver is a permanent magnet DC motor and the solar cells are fixed to a rotary axle of the tracker. Karimov et al. [130] presented a single axis tracking system using four solar modules on DC motor rotor, while another axis is manually by angles at 23°, 34° and 45°. The solar modules are mounted into two pairs where angle between them was 170°, then these modules are connected to a bridge circuit, and when output voltage from the modules is not the same, the applied voltage to

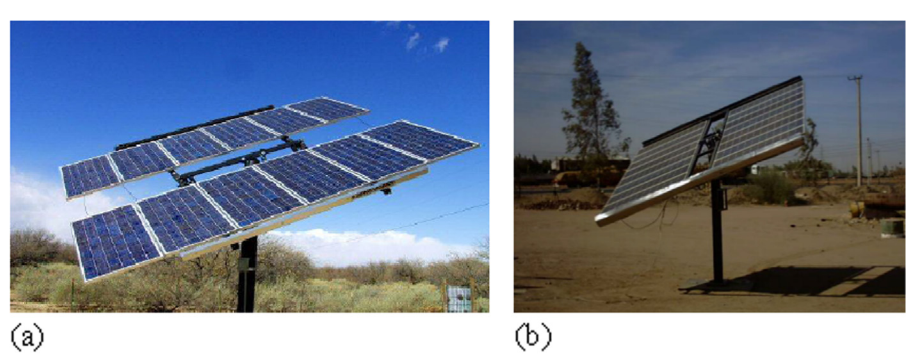


Fig. 43. (a) Universal Zomework model [14] (b) General view of the passive solar tracking system [111].

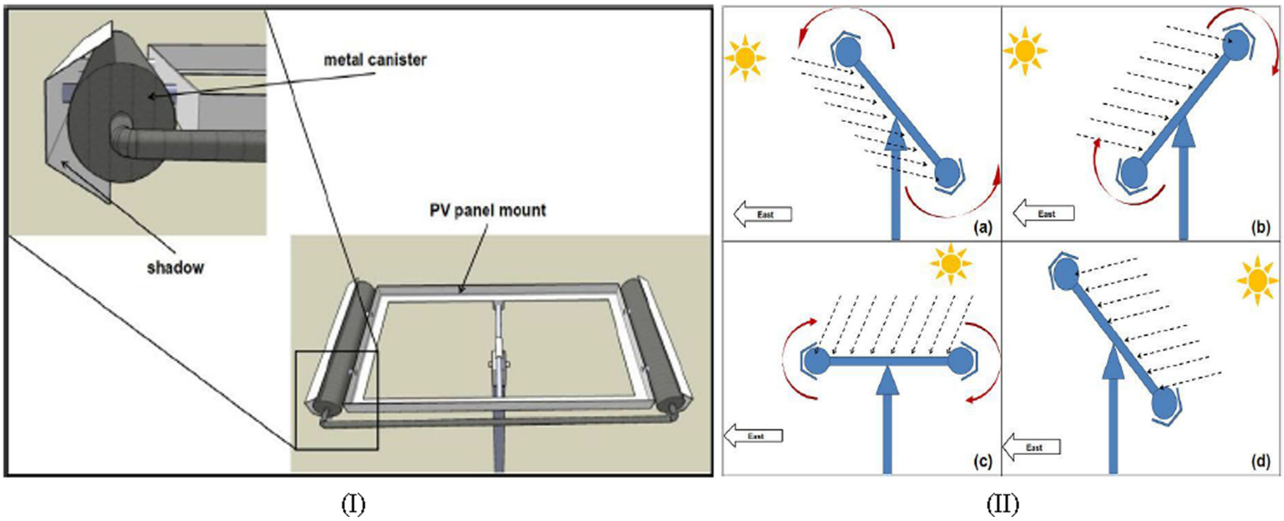


Fig. 44. (I) Design of Solar Tracker; (II) Working Mechanism of Passive solar tracker [14].

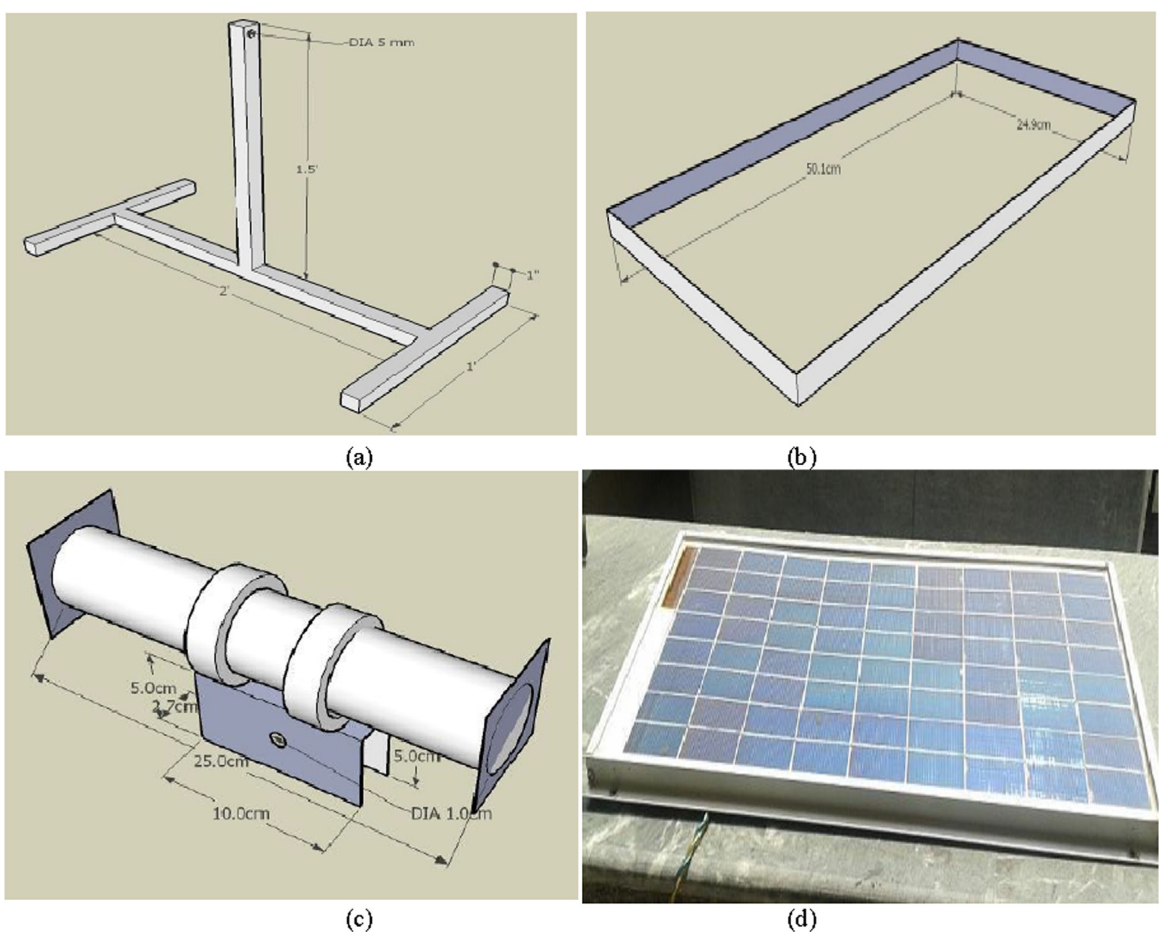


Fig. 45. Components of the solar tracker: (a) Base, (b) Frame, (c) Shafting and Bearings, (d) Solar Panel [14].

the DC motor is not zero and the motor starts to actuate. The focus of this research is the cost analysis of the system produced; where the tracking system collects 30% more energy as compared to the fixed one.

Abouzeid [40] developed new solar tracking system with a step of 15° or 7.5° and controlled by a programmable logic array (PLA) to a 8/6 four-phase, reluctance stepper motor (RSM). Fig. 42 shows an active tracking system using two opposite position sensors inserted on the tracking axe. The system used a reluctance stepper motor (RSM), which fed from a DC supply with a power converter. The converter is switched and controlled using control circuit with a programmable logic array (PLA) chip [40]. Gordon et al. [99] developed analytic formulae yearly energy as a function of radiation with three different types: stationary at tilt equals latitude, polar-axis tracking and two-axis tracking. Salawu and Oduyemi [131] presented two photodiodes separated in an enclosed rectangular structure to send signals to an electronic sun finder and solar tracking system of solar cells.

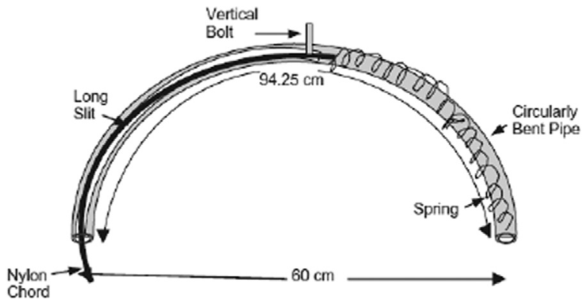


Fig. 46. Central part of the gravity based sun tracking system, consisting of a semicircular steel pipe having a long slit, a spring, a vertical bolt and a nylon chord [23].

Overall, the auxiliary bifacial solar cell based, which is the second type of active tracking system, is not common used in different tracking systems compared to the first type – microprocessor and electric-optical sensors based. Some studies considered single axis tracking system to study this type of active driver system actuating one electric motor [40,130,131] and other literature studied the driving system based on dual axis tracking [99]. The number of sensors considered in literature is also varying; some considered four solar modules as sensors located at specific angles [130] and two sensors or photodiodes [40,131].

5.2. Passive tracker

Passive tracking system is one of the solar tracking systems which depend on the thermal expansion in materials or an imbalance in pressure between two points at both ends of the tracker, where usually these materials as a fluid (liquid or gas). The fluid inserts into two reservoirs, which are opposite to each other, with the specific design in order to vaporize the fluid and change their characteristics with respect to the change in path of the sun with time. The connection between the two tanks made movement in the system by carry the condensate fluid from the highest incidence reservoir to the smaller one. The passive solar tracking system relies on a low boiling point compressed gas fluid, which cause the structure of the tracker to move to an imbalance.

One of the first passive tracking systems developed by Zomewords, which is an American company since 1969 [119]. Another passive tracking system is developed using shape memory alloy (SMA) based on axis actuators by Poulek in 1994, where SMA deformed at low operation temperatures range (below 70°C), and when it is heated above a certain specific temperature, SMA return to its original shape and SMA actuator operates as a heat engine during the thermal cycles. In addition, efficiency of SMA actuators is (∼2%) compared to bimetallic actuators [120]. The best geographic locations to use the solar passive tracking systems near the equator due to the minimum variation in azimuth and elevation angles, high solar irradiance, and it can be useful to both high power generation and isolated applications. However, there are some disadvantages for this type, namely, low efficiency, not accurate, and where the system depends on thermal expansion process. Moreover, in case of bad and adverse weather conditions, the tracking system is not propped.

Parmar et al. [14] showed passive tracker of photovoltaic module without motors, gears, and control circuits where the gravity turns the tracker, using the heat from the sun to move liquid from one side to the other side, to track the sun's path from east to west. Zomework was the first designer for using passive solar energy in solar tracking systems since 1969. Fig. (43.a) shows twelve photovoltaic modules that applied on it passive solar tracking system which delivered the same electric power as 15 photovoltaic modules. This passive solar tracking system output power increase about 25% or more compared to fixed photovoltaic module. Fig. (44. I) presents the full design of the passive solar tracking system with two metal canisters that are mounted on the both sides of the PV modules frame and kept connected together with a metal pipe. When a complete system being a fixed on a vertical pole, the shadow were fixed on both of the canisters that they cover the outer half portion of canisters. Then the panel can rotated for tracking the sun's direction and the volatile liquids filled in these canisters at high pressure. Fig. (44. II) shows the four working mechanism processes of the passive solar tracker: (a) At the beginning of the day, the sun rises from the east and the system direction is directed to the west. The sun heats the unshaded west side canister, and, then, the liquid moves into the east side canister through a copper tube rotating it to the east. (b) The control of the liquid heat process acted by the aluminum shadow plates. When one of the canister faced to the sun more period than the other, its vapor pressure increases, and forcing liquid to the cooler, shaded side. The shifting weight of the liquid causes the rack to rotate until the canisters are equally shaded. (c) As the sun path changes, the rack follows 15° per hour approximately to reach an equilibrium as the liquid moves from one side to other one. (d) The rack still complete move to the west during the rest of the day and remains during the night in the same position until the morning of the next day. The passive solar tracking system consists of main components as shown in Figs. (44) and (45): 1. The shadow bars are adjustable, and moving it with respect to the canisters, and changes during the summer and winter months to control the temperature of the liquid inside the

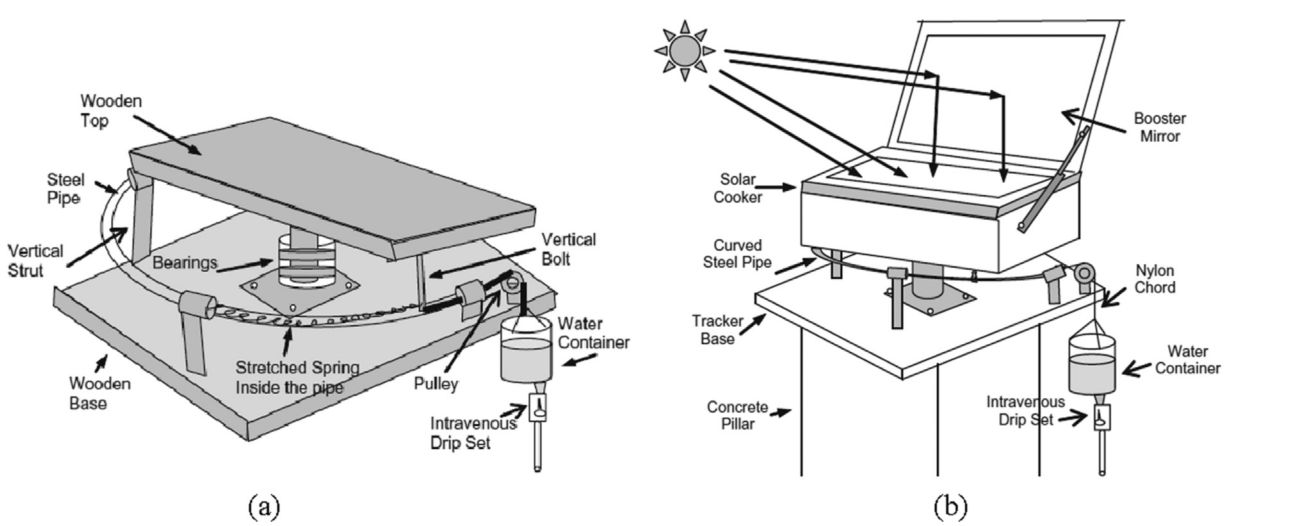


Fig. 47. (a) The complete gravity based tracking system without the tracking load, (b) The complete gravity based sun tracking system for box type solar cooker, including the solar cooker, placed over a concrete pillar [23].

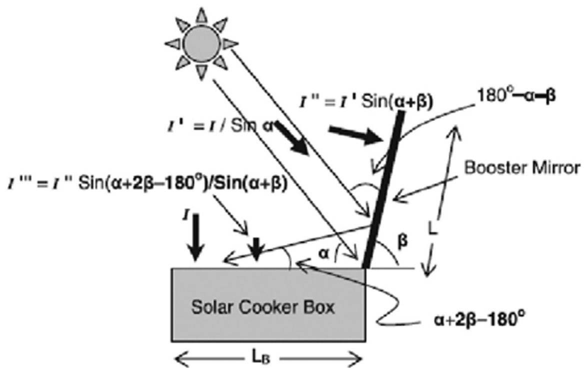


Fig. 48. Ray tracing of the component I''' of the solar radiation striking the top glazed surface of the cooker box after reflection from the booster mirror. The direct incident intensity of light on the horizontal surface is I [23].

canisters. 2. Canisters or cylinders, which coated with black color for getting best heat transfer and made from stainless steel, where the both canister connected together with pipe. When the temperature changes, a pressure difference exist and the canister filled with volatile liquid. 3. Bearing from rolling-element type to reduce the rotational friction and support both the radial and axial loads that uses balls to maintain separation between the bearing races [14].

Neagoe et al. [17] proposed a new concept for solar tracking system for flat plate solar collectors that considers the inverse tracking as a viable option for protecting the collectors against overheating based on four different programs for forward tracking, inverse tracking, maximum inverse tracking or fixing the collector. Peterson and Gray [29] tested a solar powered desalination plant ran for a 16-month period between October 2008 and February 2010 producing 3.36 million liters of permeate in 484 days of variable sunshine, in the Brisbane Botanic Gardens, Mt. Coot-tha, Queensland, Australia in order to furnish garden irrigation through dryness conditions. Fig. (43.b) shows the general view of the passive solar tracking system at Sudan [111].

Farooqui [23] presented a novel mechanism for one-dimensional tracking along the azimuth of box type solar cookers in order to eliminate the need of usual manual solar tracking. The novel method does not need any external power source since the tracking power was drawn from the gravitational potential energy stored in a spring. The prototype performance was analysed in addition to experimental results. Fig. 46 shows the central part of the basic concept mechanism of the passive solar tracking using the gravity, which consists of a semicircular steel pipe having a long slit, a spring, a vertical bolt and a nylon chord. This system inserted inside the steel pipe, which is curved. The system shown in Fig. (47.a) and (b) shows a small pipe containing both bearings which is fixed at the center of the square board and another pipe have outer diameter equal to the inner diameter of the bearings. When the top can rotate with respect to the bottom due to the pipe section of the top of the tracking system inserted into the bearings of the bottom of the tracking system. The curved steel pipe is installed horizontally through three struts on the bottom. The tracking system contains a frictionless pulley through another strut near the end of the steel pipe. In addition, the nylon chord connected to a water container and an intravenous drip set added to control the rate of water discharged, which added to the bottom of the water container. The vertical bolt top end connected to the steel rod, which is moveable through the slit in the steel pipe and inserted inside a loose hole in the rectangular wooden board (top). When a force is applied to the nylon chord, the board moves along with the bolt. Fig. (47.b) shows the complete tracking system to the box type solar cookers that placed over a concrete pillar. Fig. 48 illustrates an importance of ray tracing calculations to optimize the length of the booster mirror [23].

In summary, passive tracking system is considered as the third in ranking out of the seven types of solar tracker drive systems, which has been investigated through the present study by statistically ranking the different types of tracker drive systems mentioned in the recent research articles published as shown in Fig. 5. This tracker system, taking the advantage of changing physical properties of fluids towards solar energy in tracking the sun, studied in literature through investigating different medium; for instance, moving liquids that are easily affected by sun rays (volatile liquids) [14,119] and using gravitational potential through mounting springs [23]. In addition, myriad applications has been considered in literature implementing the passive tracking system such as photovoltaic panels/modules [14,119], flat plate solar collectors application [17], and even in solar desalination systems [29]. The

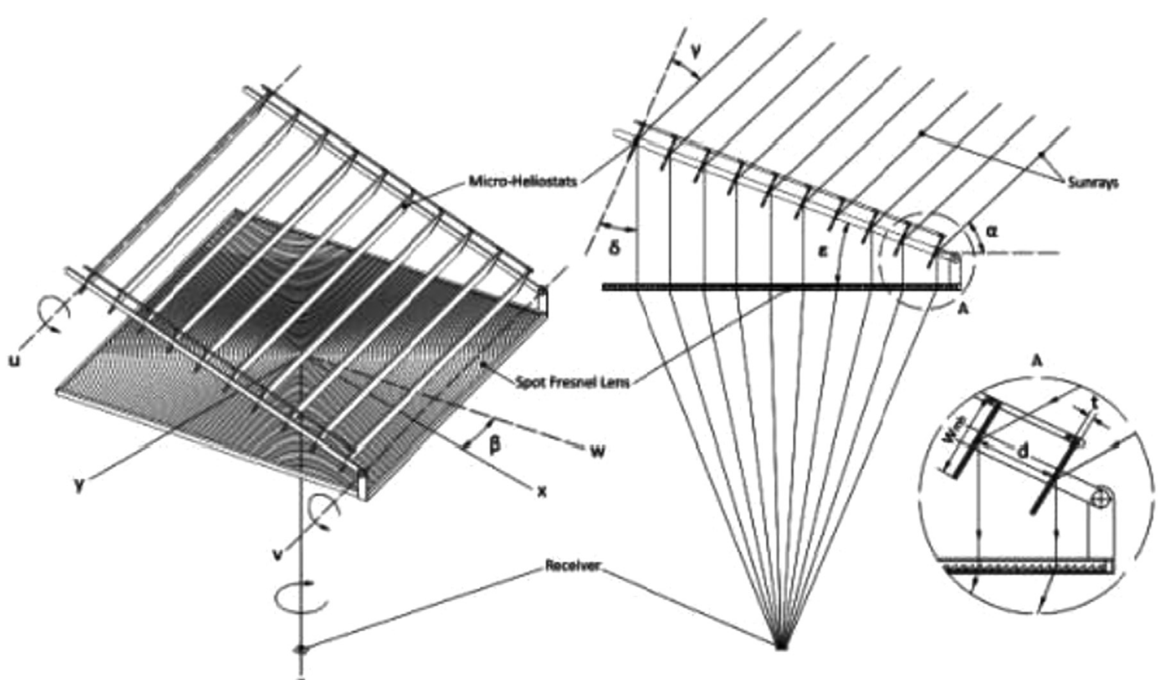


Fig. 49. Semi-passive solar tracking concentrator encompasses a micro-heliostat array, a Fresnel lens and a receiver [112].

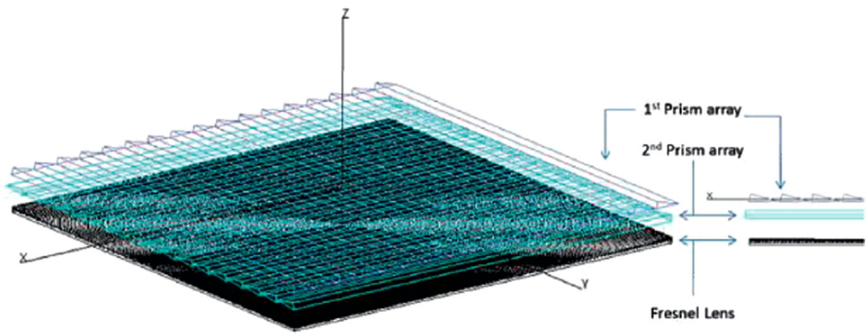


Fig. 50. Semi-passive solar tracking concentrator formed by two prisms arrays and a Fresnel lens [61].

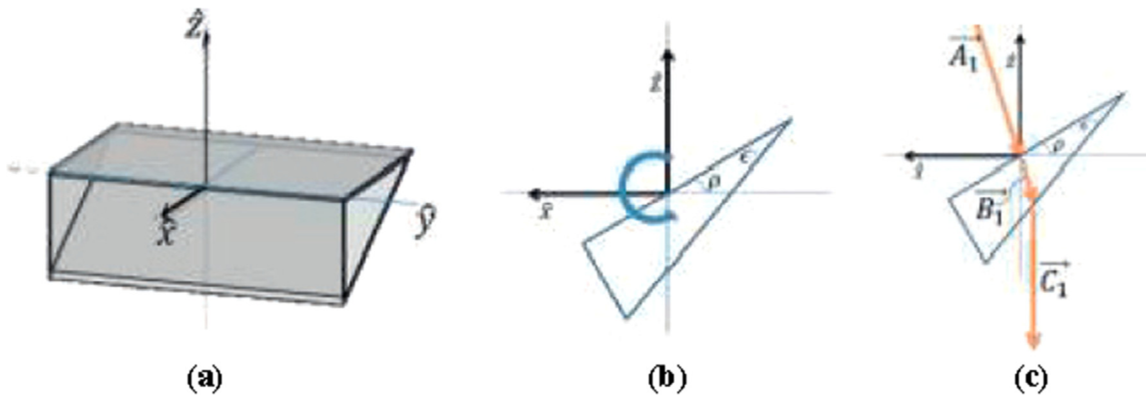


Fig. 51. (a) Spatial orientation of a prism from 1st array, (b) Prism rotated ρ, (c) beam's path through prism 1 [61].

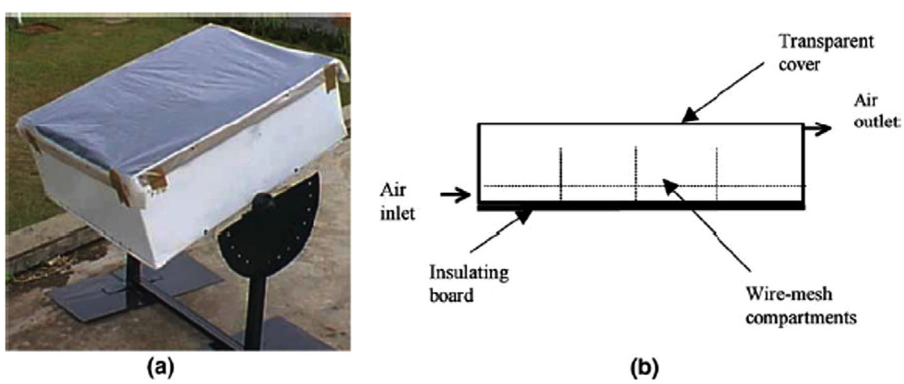


Fig. 52. The solar dryer used in drying experiments; (a) Pictorial view, (b) cross-section view [38].

research in this type is increasingly attract scholars because of the plentiful advantages of using it instead of using the complicated systems that utilize control circuits, sensors, gears, motors and so on.

5.3. Semi-passive tracker

A semi-passive tracking system is a technique where the solar tracking concentrator can track the sun and keep the sun's rays perpendicular to the absorber's cross-sectional area with a minimal mechanical effort and reduced movement for sun tracking. The system is consisted of a micro-heliostat array, a Fresnel lens and a receiver.

León et al. [112] proposed a system of a semi-passive solar tracking concentrator, which is an optical system used to concentrate solar irradiant while tracking the sun with minimum mechanical movement. The main components of the system are shown in Fig. 49 and consists of micro-heliostat array, a Fresnel lens and a receiver. The function of the micro-heliostat array is to track the sun location and reflect solar beams toward the Fresnel lens. The lens maintained horizontally in order to decrease the wind loads along all the system. Regarding the receiver, it is kept stable and stable placed on the lens focus, and, as a result of releasing receiver weight, the power needed for the system motion will be minimized [112].

León et al. [61] proposed a novel semi-passive solar tracking concentrator (SPSTC) for tracking the sun through two independent arrays of acrylic prisms. The prisms applied to refract sunlight by the means of rotating said prisms for redirecting solar beams as required. This optical system can collect the highest feasible energy by focusing sun irradiation with minimum motion needs. By the means of two layers of poly methyl methacrylate (PMMA) prisms, the received solar beams redirected vertically upon a fixed Fresnel lens. In Fig. 50 illustrates two arrays of prisms perpendicular to each other just above Fresnel lens, which kept fixed horizontal placement. According to the Fig. (51.b), each prism in the above array rotates over the y-axis used for removing the one of the solar beams direction vector components, Fig. (51.c), leaving ideally $C_{I,X} = 0$. Subsequentlly, C_I rays gets in the second set of prisms rotated around x–axis for removing the other direction vector

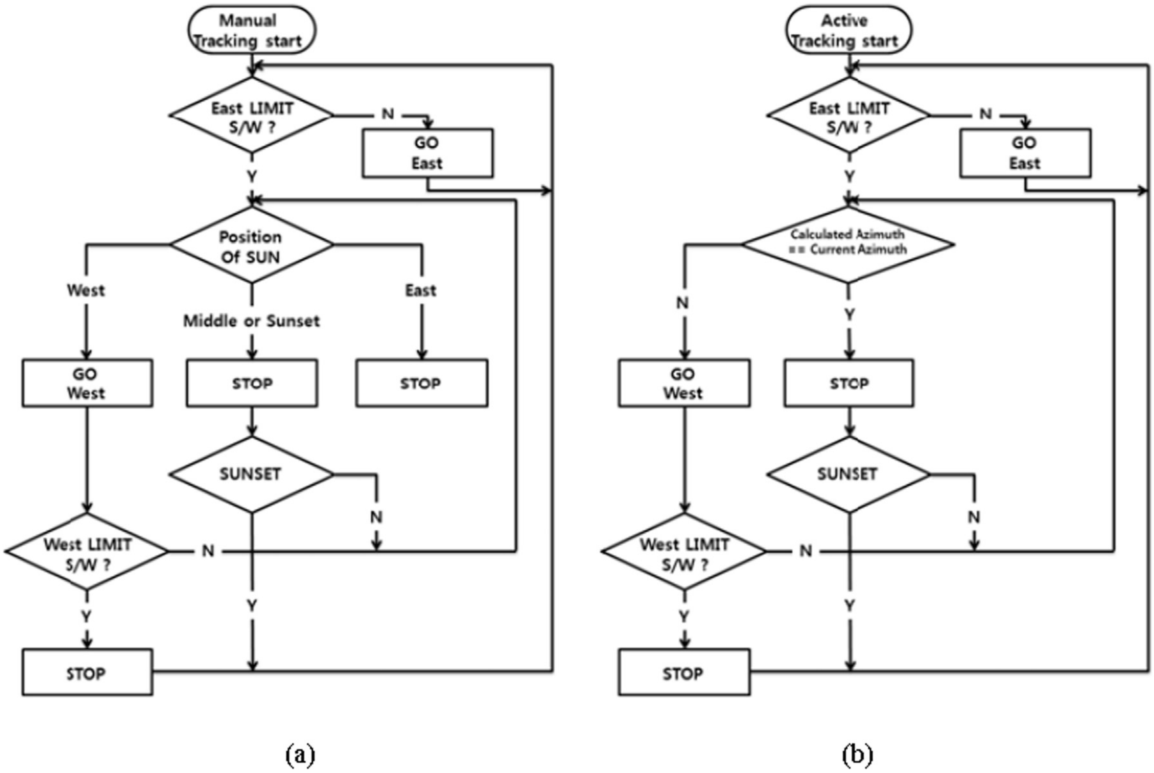


Fig. 53. Tracking Algorithm Flow Chart (a) Manual Tracking Algorithm (b) Active Tracking Algorithm [20].

component. As a result, the resultant ray will leaves perpendicular to the plane XY downward with one fixed direction. This type of compact lens focuses and concentrates solar energy in a smaller area [61].

Overall, semi-passive tracker systems are not widely used or studied in the literature compared to active trackers or the passive one; it is considered as a unique tracker type. As mentioned, the substantial purpose of this type is to reduce the mechanical energy consumed by the traditional/ conventional trackers. The systems studied by researchers mainly use either micro-heliostat array [112] or two layers of poly methyl methacrylate prisms [61] to reflect solar beams upon Fresnel lens aiming to reduce the mechanical system movements.

5.4. Manual tracker

Manual solar tracker is a method where the system can track the sun angle from season to season with manual tilt angle changing per seasons using a manual gear for ease of the system construction and maintenance. One of the significant advantages of the manual tilt angle axis as the secondary axis in the dual-axis tracking systems is cheaper than used in the previous types by implementing a second motor.

Mwithiga and Kigo [38] designed a small solar dryer with limited sun tracking with an incremental of 15° to dry grains and parchment coffee which takes 2–3 days instead of 5–7 days. The performance of the tracking system is tested with the horizontal either once, three, five or nine times a day. Fig. 52 shows solar dryer which consists of a flat plate steel absorber into a topless box 8×1 m and 30 cm high and able to track the sun at east–west direction using a selector disc on the stand that allowed the tilt angle change with the horizontal axis to be easily adjusted with an incremental at least 15° [38].

Choi et al. [20] manufactured manual and active tracking algorithms for floating photovoltaic system to develop an effective azimuth angle algorithm. Fig. (53.a) shows a manual tracking algorithm for tracking and detecting the position of the sun using photovoltaic sensor. When the west limit switch is turned on (sunset), the sensor stops operating and moves to the position of the east limit switch for operation on the next day (sunrise). Fig. (53.b) shows active tracking algorithm that tracks position of the sun by computing hourly azimuth angle based on astronomical position. Fig. (54.a) shows the test of tracking-type floating photovoltaic model. When forward/reverse button pushed, the rotor operated and the button used for manual operation during emergency as shown in Fig. (54.b). Fig. (54.c) presents manual tracking algorithm test to the movement for rotating the PV structure using an optical sensor (azimuth sensor) and halogen lamp as an equivalent of the sunlight. It is moved left and right of the optical sensor to test the forward and reverse rotation of the PV rotor. Active tracking algorithm was moved using timer where the time and angle are calculated to the forward and reverse rotation from east to west during the whole day as shown in Fig. (54.d) [20].

To conclude, the manual tracker system is not a widespread type of tracker systems through the literature similar to the semi-passive one. The system depends on manually adjusted to reduce the complicity, make the system easily towards maintenance, and also reduce the overall cost of the system's components. Few studies focus their research effort towards this particular type limiting their work in some applications such as solar dryer (similar to solar cooking applications) [38] and in photovoltaic systems (PV) using as a floating system [20].

5.5. Chronological tracker

A chronological solar tracking system is a time-based tracking system where the system collector or module moves with a fixed rate and a fixed angle throughout the day as well for different months. The motor or actuator is controlled to rotate at the low rate (15° per hour approx.). This tracking system is a typical open loop control tracker based on a chronological model of its motion. One of the main advantages of this system, which is more energy efficient because no energy losses at this tracking calibration due to low tracking error [88].

Roong and Chong [2] designed and constructed laboratory-scale single axis solar tracking system to PV panel using chronological method with angle of rotation 15° per hour. Fig. (55.a) shows the actual

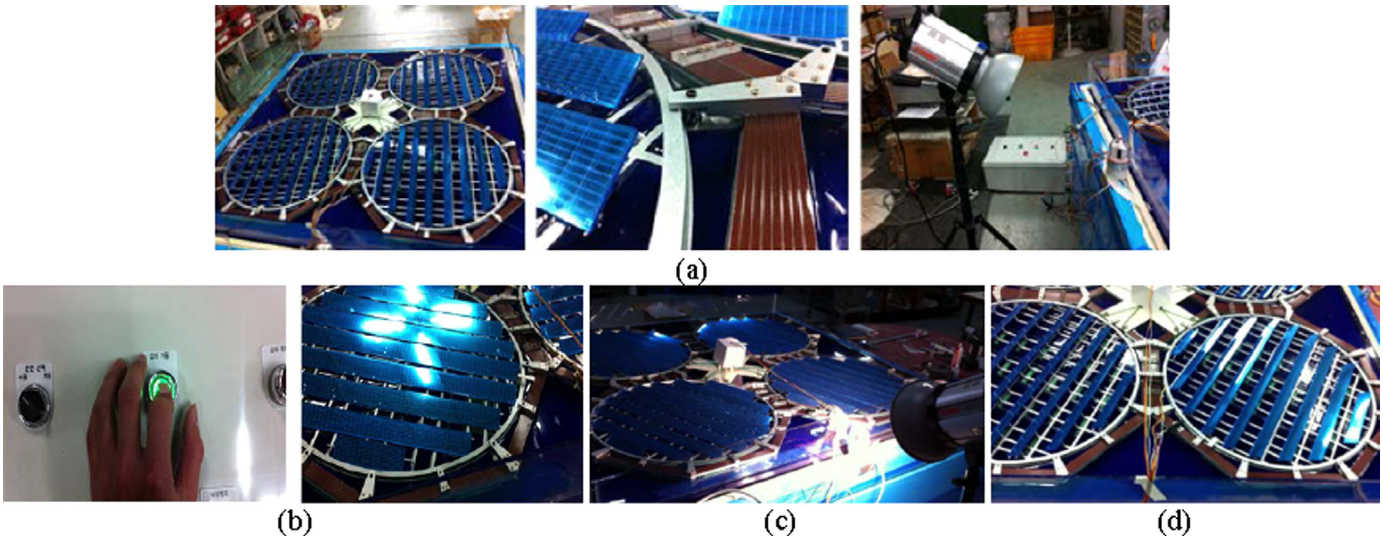


Fig. 54. (a) Test of Floating Photovoltaic Model (b) Forward and Reverse Rotation Control using the Control Panel (c) Solar tracking test to manual tracking algorithm (d) Moving the East by the Limit-Sensor to active tracking algorithm [20].

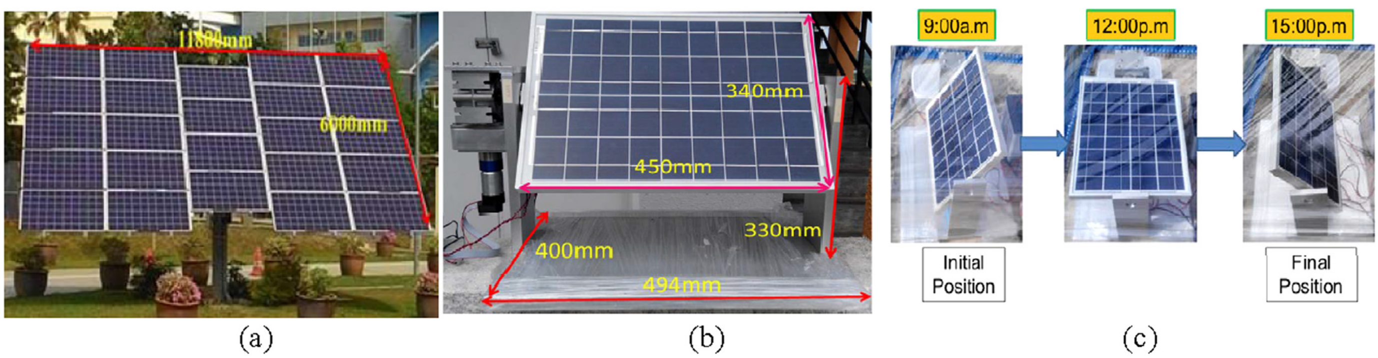


Fig. 55. (a) Solar tracking system plant in FKE, UTeM (b) Laboratory-scale solar tracking system (c) The position of the solar panel from 9:00 A.M. to 15:00 P.M. [2].

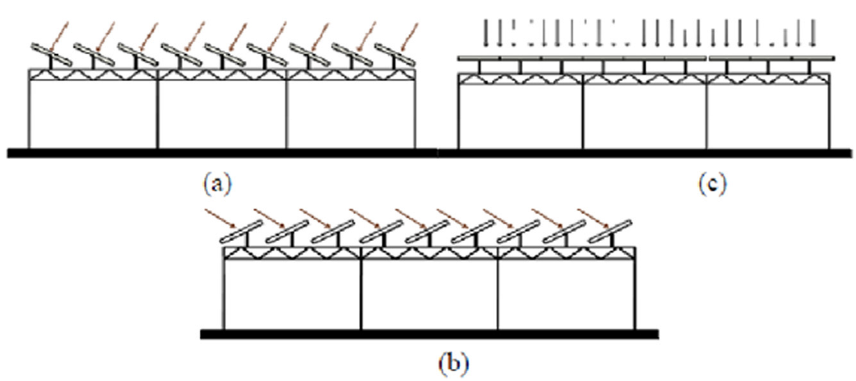
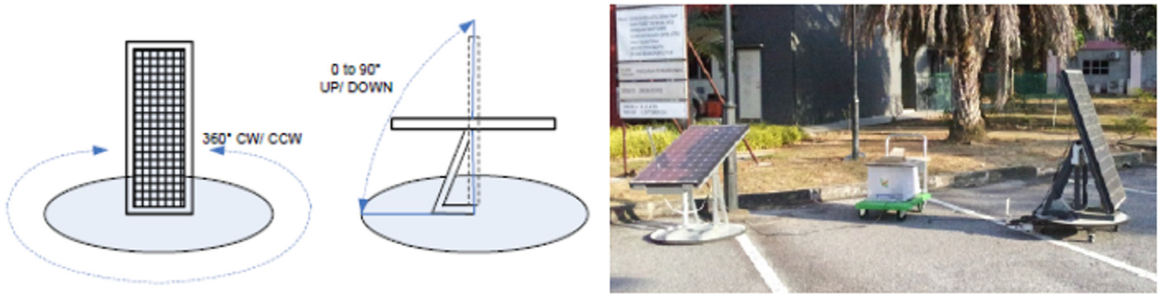


Fig. 56. (a) Panels oriented towards morning sun. (b) Panels oriented directly under midafternoon sun. (c) Panels oriented towards afternoon sun [31].

solar tracking system plant in FKE, UTeM with the total surface area is around 70 m^2 and the dimension of 11.8(l) x 6(w) m. The laboratory-scale solar tracking system scaled down to ratio 462: 1 with the dimension of the laboratory-scale solar panel is 0.34(l) x 0.45(w) m as shown in Fig. (55.b). The experiments acted to the solar panel for 5 days from 8:00 P.M. to 15:00 P.M. where the solar tracker angle of rotation is 15° per hour as shown in Fig. (16.c) [2].

M. and Abdul Rahman [31] determined the efficiency of poly-crystalline, mono-crystalline and amorphous silicon solar module using single-axis time/date solar tracker under climate of Malaysia. Fig. 56 shows the basic design diagram of the PV panels tracking system to the sun according to three positions in the morning, mid afternoon and evening to allow the PV panels to set perpendicularly toward the sun [31]. Sidek et al. [66] designed dual solar tracking using an electronic control system and the algorithm based on the GPS and astronomical equation. In addition, the microcontroller based tracking system embedded with a PID controller. Fig. (57.a) shows the biaxial solar tracker structure design using mechanical design software, SolidWorks to the photovoltaic module and two systems fixed-tilted PV panel and the solar tracker system are compared by the power generated between them as shown in Fig. (57.b) to reach the performance of the solar tracker system [66].

Subsequently, chronological solar tracking system is common among researchers to study and investigate, based on the literature



(a) (b)

Fig. 57. (a) Structure of the solar tracker. (b) Data collection setup of the two systems. [66].

introduced in this study. As mentioned, the tracking system relies mainly on the chronological data inserted into the system to allocate the accurate/precise position of the sun to be tracked. Some scholars shade the light on implanting this type of tracking system on single axis solar tracking [2,31] while others considered the dual axis tracking system to study the performance of this tracking drive type [66]. It is worth mentioning that most of the studies, investigated this type of tracking drivers, directed their interest for photovoltaics PV applications [2,31,66].

6. Conclusion

The conclusion from the literature review that solar tracking systems could improve the efficiency and power yield of the solar applications. The main objective of this study is to investigate the feasibility of the solar tracking systems using different systems of axes and various regions of the world. The solar tracker drive systems encompassed five categories based on the tracking technologies, namely, active tracking, passive tracking, semi-passive tracking, manual tracking, and chronological tracking. Furthermore, the present work introduces a review of the major applications and systems design for solar tracking systems, which developed over the past 50 years. The most conclusion points as:

- There are 42.57% of the studies discussed and presented single axis tracking systems while 41.58% of these studies to the dual axes tracking systems. This lead to the difference between the single axis tracking and dual axes are very close because the gain from the power output increases covers by the cost increases also.
- The significant usage in the drive solar tracker to active tracker type by 76.42% while in the second most impact is the chronological solar tracker by 7.55%. The active tracker is major type used in many research areas and application in the real field due to the high efficiency of the gain output from it and the decrease in the overall cost.
- The percentage of the solar tracking techniques in the recent studies, where Azimuth and altitude tracking achieve 16.67% in usage, Horizontal tracking by 16.67%, Azimuth tracking by 10%, and polar tracking by 4.44%.

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