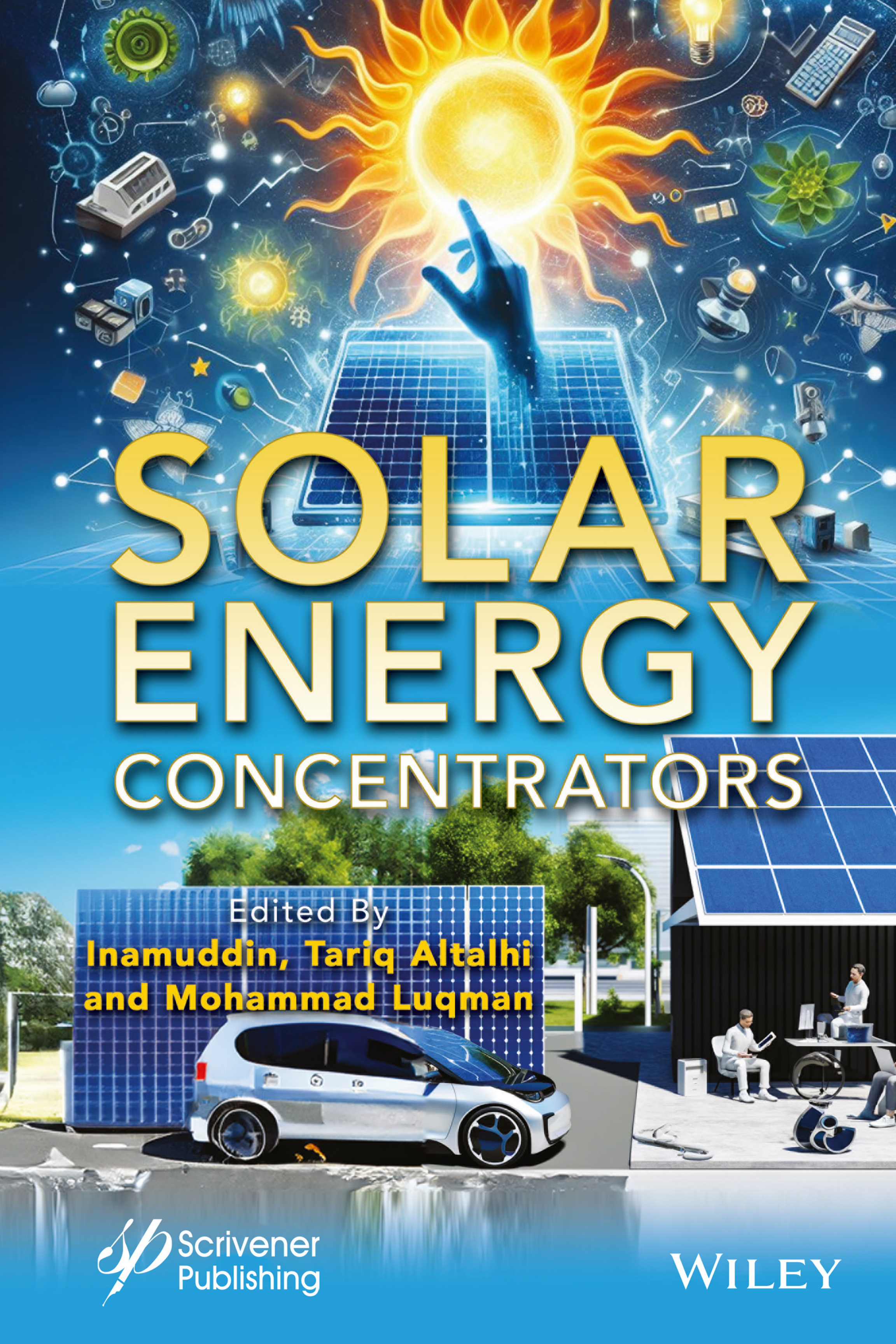

SOLAR ENERGY CONCENTRATORS

Edited By
Inamuddin, Tariq Altalhi
and Mohammad Luqman

Scrivener Publishing

WILEY

Solar Energy Concentrators

Scrivener Publishing
100 Cummings Center, Suite 541J
Beverly, MA 01915-6106

Publishers at Scrivener
Martin Scrivener (martin@scrivenerpublishing.com)
Phillip Carmical (pcarmical@scrivenerpublishing.com)

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Essentials and Applications

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This edition first published 2024 by John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA and Scrivener Publishing LLC, 100 Cummings Center, Suite 541J, Beverly, MA 01915, USA

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Wiley Global Headquarters
111 River Street, Hoboken, NJ 07030, USA

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Library of Congress Cataloging-in-Publication Data

ISBN 9781394204328

Front cover images supplied by Pixabay.com
Cover design by Russell Richardson

Set in size of 11pt and Minion Pro by Manila Typesetting Company, Makati, Philippines

Printed in the USA

10 9 8 7 6 5 4 3 2 1

Contents

Preface

Around the globe, there is a tremendous drive to investigate the viability of utilizing solar energy, particularly in regions with temperate zones. The usage of solar energy in many sectors has grown over the years. The ongoing quest for an alternate energy source in response to the apparent depletion of fossil resources is the driving factor behind this transition. Fossil fuels are far more widely used now than ever before despite their rising price. Although all forms of renewable energy are accessible, solar radiation is the most prevalent and easily accessible. Using solar energy for higher processing temperatures is difficult despite it being the most common clean and affordable renewable energy source on the planet. For this, solar energy concentrators (SEC) are a promising technology that could be used to harness both heat and electricity for diversified industrial operations. SECs are devices that harvest solar radiation and direct it to a single point of concentration. This book presents the most up-to-date fundamental strategies for the collection of the sun's radiation. Moreover, SEC's technical summaries are also evaluated concerning the ongoing international assignments. Prominent applications are also featured to show the reader the scope of the SEC's applicability. The potential implementations demonstrate that CSE can be employed in a wide range of systems and may offer considerable economic and environmental advantages. By going through this book, one can learn more about the significance of solar energy concentrators, the technologies that are related to them, and the plethora of applications. For those interested in this field, this publication is a great resource for academics, researchers, environmentalists, and professionals.

Chapter 1 highlights the optical techniques of solar power concentrators (CPS) such as solar tracking systems, mirrors, and lenses which enhance the efficiency of CSP. Various mathematical models are explored to understand and calculate the heat and electricity generation in CSP. The study emphasizes CSP's potential as cost cost-effective, eco-friendly, and easily accessible solution for a clean and sustainable energy future.

Chapter 2 the increase of electrical conversion efficiency (ECE) of solar cells is one of the main objectives, This chapter focuses on solar energy concentrators also called PV concentrators to increase on one hand the ECE of a solar cell and to reduce the cost of its manufacturing using less silicon material.

Chapter 3 entails the solar energy concentrators, their principle, and main components such as primary and secondary concentrators. Types of energy concentrators such as parabolic trough and dish concentrators, hyperboloid concentrators, Fresnel lens imaging, non-imaging concentrators, compound parabolic concentrators, and quantum dot concentrators. Thermodynamic and optical limits of solar concentrators are also discussed.

Chapter 4 explores the basic principle, ideal solar concentrator, and limitations factors faced in solar concentrator applications such as photovoltaic efficiency, absorption loss, design limitations, scaling, the effect of temperature, thermal properties, and concentration ratio along with economic aspects, and future perspectives.

Chapter 5 evaluates simultaneously based on ten decision criteria by constructing a hierarchical structure of the criteria for four different solar concentrator mechanisms. The applied methodology and the structure aim to provide a basis for feasibility studies in the field.

Chapter 6 offers a historical survey of solar concentrators, covering their evolution from early models to modern designs. It investigates the principles, benefits, and constraints associated with diverse types of solar concentrators, such as Parabolic troughs, Fresnel lens reflectors, Dish concentrators, and Heliostat solar concentrators with central receivers. Moreover, the chapter emphasizes recent progress in these concentrators, showcasing the latest advancements in solar energy research.

Chapter 7 provides an overview of the available and possible thermal storage materials used in concentrated solar power (CSP). Various topics covered are the fundamentals of Solar Power Concentration, types of CSP technologies, Energy storage techniques for CSP systems, integration of thermal storage materials in CSP systems, and different kinds of thermal storage materials for CSP and their various classifications. Additionally, the strengths and challenges of different thermal storage material types, as well as their implementation drawbacks in CSP technologies, were also emphasized.

Chapter 8 discusses the effectiveness of doping Uranyl ion in luminescent solar concentrators, over organic dyes. Besides discussing the effect of alkali in increasing the efficiency and role of concentration of Uranium luminophores, the concept of co-doping and its role in increasing effectiveness toward increasing efficiency is also described broadly.

Chapter 9 Solar energy concentrators have the remarkable potential to revolutionize the global energy industry by making solar technology more affordable without compromising its performance. The key problem is the high initial cost of constructing the system. Solar concentrators play a vital role in optimizing the efficiency and affordability of solar energy utilization. Solar concentrators are experiencing growing adoption across various solar energy domains, including concentrated solar photovoltaics, solar steam power generation, solar energy storage, solar cooking, and more.

Chapter 10 explores solar energy and concentrating solar power (CSP) applications. It focuses on molten salt thermal storage systems for preserving CSP-generated energy. Technological advancements like upscaling, alternative molten salt options and single-tank storage solutions are examined, promoting a sustainable solar energy future.

Chapter 11 discusses the conversion of sunlight into high-temperature heat, which is then utilized to drive various chemical processes to produce synthetic fuels like hydrogen and Methanol. This technology presents a promising pathway to decrease greenhouse gas emissions and reduce dependency on fossil fuels. Synthetic fuel production using this technology is eco-friendly.

Chapter 12 explores the significance and role of solar concentrator-based daylighting systems (DLS). Different solar concentrators such as reflecting concentrators and heliostats are deliberated. Modern-day lighting systems, their stacking theory, design, and various efficiency factors are deliberated as well. The role, design, and efficiency parameters of optical fiber in solar concentrators DLS are discussed as well. Current problems are future perspectives are discussed too.

Key features:

Provides a broad overview of solar energy concentrators (SEC)
Outlook for the essential insight of collection of renewable energy
Presentation of SEC's applications in various domains

1

Basics of Solar Energy Concentrators

Habiba Mushtaq, Amina Khan and Haq Nawaz Bhatti*

Department of Chemistry, University of Agriculture, Faisalabad, Pakistan

Abstract

The expenditure on fossil fuels drastically affects our global environment and requires cost-effective and eco-friendly energy resources. Solar power concentrators have been gaining ever-increasing attention from academic researchers and industrial developers owing to their stationary feature for solar energy collection with higher efficiency and the fact that they are economically feasible, have a green nature, and are easily accessible. The solar energy concentrator captures the sun's energy with large lenses or mirrors that focus the sunlight onto the receiver surface. It first transforms into thermal energy that rotates the generator's turbines to produce electricity. Solar concentrators enhance irradiance by implementing optical techniques like a tracking system, lenses, and mirrors. Various mathematical models and computational methods are used to view the theoretical detail and calculate heat and electricity generation in CSP. This study aims to supply a broad understanding of CSP-based theories and models and provide help to researchers, engineers, etc. The CSP has the potential to reconstruct renewable energy resources and to transition globally toward a clean and sustainable energy system in the future.

***Keywords*:** Azimuth, CSP, radiations, power plant, trackers

1.1 Introduction

There is a need for substitute energy sources to meet the demand for power in the world due to the increasing emergence of appliances such as computers, mobile phones, televisions, etc. There is a need to enhance the efficiency and lower the price of electricity production. Different alternatives are used to meet this requirement [1]. Concentrating solar power (CSP) is

**Corresponding author*: hnbhatti2005@yahoo.com

Inamuddin, Tariq Altalhi and Mohammad Luqman (eds.) Solar Energy Concentrators: Essentials and Applications, (1–32) © 2024 Scrivener Publishing LLC

a system that produces power. It transforms solar energy into heat energy through a solar concentrator and then heat energy into power generation. The photovoltaic system is a comparatively different system than concentrating solar power. The heat energy from the sun is utilized by the CSP system rather than the photon energy used by the PV system, as shown in Figure 1.1. CSP has four main categories: (1) parabolic trough, (2) power tower, (3) linear Fresnel, and (4) dish. The dish uses the Stirling engine system to concentrate thermal energy. The CSP system consists of mirrors or lenses to target a vast area of sunlight, while solar power energy (SPE) focuses on confined spaces. A heat energy source is enlarged when solar power plants are coupled with a fossil fuel burner [2].

The previously published data have demonstrated that solar energy photovoltaic transformation productivity increases when radiation intensity falls on a photoelectric converter, and the productivity of solar energy photovoltaic conversion increases, similar to transformation into SPE. The capability of solar energy photoelectric conversion increases with the high concentration of radiation descending upon the solar converter [3]. Lowering energy production costs and improving efficiency using concentrated solar radiation are feasible. There is another alternative way to increase power capacity, that is, by photovoltaic cells, which can be adjacent to the CSP system. One of the main options is to use high-energy photovoltaic cells depending on solar cell arrangement with big solar energy concentrators. These concentrators work by collecting rays that have been refracted or reflected into a central axis focal point, where a radiation converter-receiver is mounted [2].

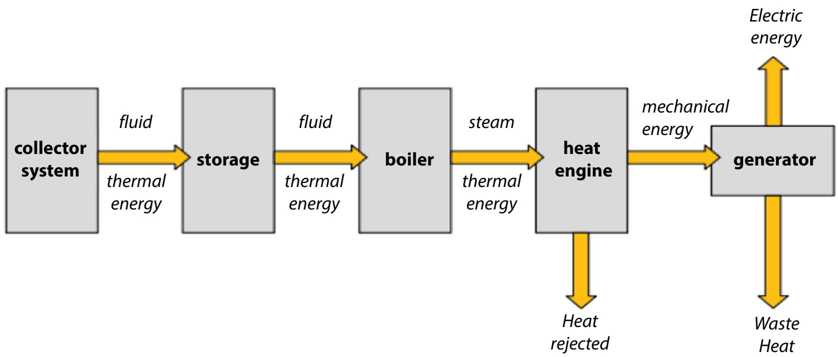

Figure 1.1 Mechanism of a solar energy concentrator.

1.2 Solar Tracking Systems (STS)

Many scholars have continuously developed solar trackers to facilitate the productivity of solar energy captured during dawn. To ensure optimum energy capture, solar cells are positioned optimally in the daytime. Efficiency using the sun tracking approach is 6.7% greater than efficiency using the fixed angle. The solar panels would be placed so that sun tracking would maximize electricity and boost production by 30%–40%, which is substantial enough to make sun tracking a practical option. This system keeps the solar insolation perpendicular to the solar radiation beam in solar cells. Solar cells are projected to carry the solar beam vertically to the PV panel. The position of the tracking method can attain the optimum angle of incidence. The astrotracker's role ought to reach an optimum angle of incidence, and the PV panel generates the highest amount of electrical energy.

The accurate positions of the tracking system are solar irradiance, solar azimuth angle, elevation angle, inclination angle, declination angle, and zenith angle. The altitude and azimuth angle are essential to demonstrate the sun's position [4, 5]. The light source's solar power and luminescent flux compute the solar irradiance. Solar tracking systems can move automatically or manually. A solar tracking system usually involves several components, including one or two motors, several kinds of optical sensors, and a backup energy source. These elements are categorized according to numerous parameters like the force that moves their portable devices and the mode of working.

1.2.1 Types of Solar Trackers Based on Techniques

A solar tracker is divided into three main types based on technologies that direct the Pv panel fluctuation: (1) passive tracker, (2) active tracker, and (3) chronological tracker system [5, 6]. Table 1.1 shows the comparison between these tracking systems.

1.2.2 Passive Solar Tracker

Without mechanical drives, it can point its sensor units toward the solar radiation beam. The passive tracker uses direct energy generated by the sun's thermal energy, as shown in Figure 1.2. These trackers typically have two actuators loaded with expandible gas or an alloy. This tracker has used the principle of thermal expansion or variation in pressure between two sites at the end of this system. When the position of the PV panel is

Table 1.1 Differences between different solar trackers.

Technology	Description	Advantages	Disadvantages
Passive	• Thermal expansion material or imbalance in pressure between two points at the both end of tracker	• Work without using motor or actuators • Easy installation • Low maintenance cost	• Strong dependance in weather condition • Low in accuracy
Active	• Use sensors and motor	• More accurate • Efficient in tracking the position of sun	• Require the extra power consumption • Not very accurate under cloudy day
Chronological	• Time based tracking system • Rotate at 15° per hour	• No energy looses • Low tracking error	• Continuous rotation requires more energy • Unnecessary work under cloudy day

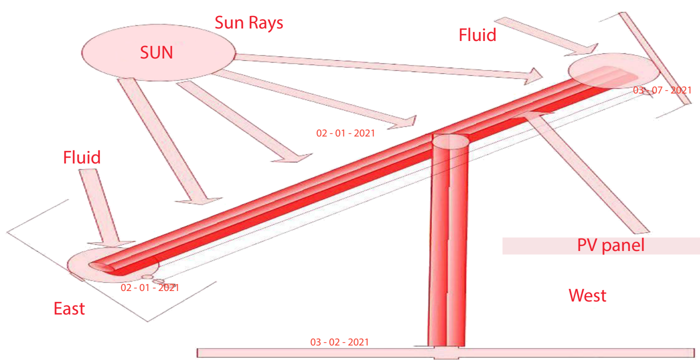

Figure 1.2 Passive solar tracker.

erect to the sun, both sides of the tracker are balanced. One side of the tracker becomes heated, expanding and coming into touch with the other when the sun rotates, which causes the PV panel to rotate. Zomeworks Corporation unveiled the first passive solar tracking device for commercial use in 1969. Compared to fixed PV panels on Zomeworks Track Racks, PV panels with tracking systems can produce 25% more electricity [7]. This system makes operation more straightforward because most include two actuators competing and balanced by equal illumination. A passive tracker is affordable due to cheap and easy repairs but is less accurate. The tracker has a shock absorber that blocks the tracker from the sudden movement of the wind [8]. However, the precision of this method of tracking the sun could be better, and it mostly depends on the local weather. The site chosen for installing the solar tracker is essential since it must get enough continuous sunshine for an effective heating method [9].

1.2.3 Active Solar Tracker Active

This system has an electric system and a photoresistor, which controls the motor to regulate tracker movement. The astrotracker continually determines the location of the sun using the available sensors. A sensor will cause a motor or actuator to move its fixture in response to sun radiation [9]. If the sun's radiation is not right on the tracker, one light sensor will be illuminated differently from another. The direction is calculated using the difference when the tracker must be pointed perpendicular to the sun. A light-dependent resistor with a variable resistor, which relies on radiation incidence, is a commonly used photo sensor. Due to an electrical component that is climate- and lightning-sensitive, this device has a low level of reliability. It operates on the sensor. Thus, its tracker may become blocked, causing significant issues and impeding energy production. As a result, this system is constantly under observation [10]. It is classified into four types placed on their tracking techniques. Microprocessors, electro-optical sensors based on date and time, auxiliary bifacial solar cells, and a combination of the three types are all available. Based on the technologies, the solar tractor is divided into two major groups: single-axis tracker system (SATS) and dual-axis tracker system (DATS) as shown in Figure 1.3 [6].

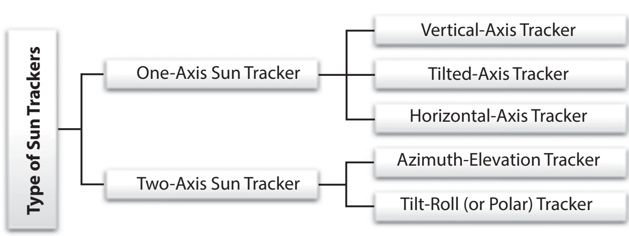

Figure 1.3 Different types of solar tracking methods.

1.2.3.1 The Single Axis of the Solar Tracker

The axis rotation serves as the one variable quantity and process of the sun in one way. It has two groups: horizontal single-axis tracker (HSAT) and vertical single-axis tracker (VSAT). The horizontal tracker locates the sun's approaches to the south and north and the sun's seasonal track. Vertical systems track the sun toward the east and west and the sun's daily direction. To maximize energy harvesting, a PIC microcontroller-driven system was expanded. The two PV panels are placed next to one another in a triangle. The two quantities of threshold control the activity of PV panels. The first threshold and accessibility of solar energy sets the regulation of direction. When overcast or raining for an extended time, another threshold is used to switch off the surrounding [11].

The economic system was designed into the system, but there is a problem when the system is not performing after nightfall. The PV panel is receded on the east side for other tracking days. A GPS-based solar tracker system is constructed to shift the vertical solar, followed by the sun's azimuth angle. They contrast the output of two solar cells that were positioned differently. With the help of the solar tracker system, the initial energy cell is deposited and erected, and another solar cell is mounted horizontally in the meantime. According to the findings, the moderate output power of the first solar cell is roughly 22%, which is more significant than another solar cell. In addition, scientists claim that incorporating GPS and astronomical computations speeds up solar tracking systems [5, 12].

1.2.3.2 Dual-Axis System Solar Tracker

It has dual parametric quantities, which act as a rotational plane in this system, and have both vertical and horizontal axis. The daily and annual motions are two movements in which the earth follows a complex action. Due to daily activity, the sun comes out higher than the earth at an east-to-west altitude. While travelling from east to west, the slope of the sun is concerning to a particular degree as part of its annual motion increases the effectiveness and encourages the usage of this tracker [11]. The system has two varieties: polar altitude and azimuth altitude [11]. This tracking system's components consist of a controller, two motors, and four light-dependent resistors (LDRs) [13]. The principle of a DAST system depends on the working of microcontrollers. A microcontroller is utilized to evaluate the algorithm to evaluate the location and direction of the PV panel. This method can work even in lousy situations and does not depend on the sky clarity and sun altitude. Energy efficiency will be increased up to

26.9% with the help of a GPS sensor and a sun trajectory algorithm with a dual tracker [14]. The suggested system may operate without user input and be installed anywhere. Due to the intricate algorithms utilized, which need lengthy computations, implementing such strategies is typically more complicated. The system's output is more effective than single-axis and fixed panels [5].

1.2.4 Chronological Solar Tracker

A chronological system moves the arrangement at a predetermined pace and angle in the daytime and over several months. It is a time-based tracking system. As a result, the motor or actuator is organized to spin steadily in one day, and the average range is 15° per hour. This system has a minute error because there are no energy losses at this tracking calibration, and this technique is more energy-competent [15]. A microcontroller is coupled to a motor driver to proceed with the PV panel in a specific way and check the sun's location [16]. The system's disadvantage is that it is susceptible to environmental factors and electric discharge. The essential advantage of this setup is that it is exact and can operate in the worst winter conditions at varied latitudes around the equator [17].

1.3 Azimuth-Elevation Sun-Tracker

The CPV system enhances solar energy efficiency by up to 46% by upgrading the multi-junction solar cell, thermoregulator, and DAST method compared to the conventional method and the concentrator PV requisite reflector or lenses to fall sunlight on the multi-junction solar cell [18]. These systems and tilt-roll (polar) are primary sun-tracking mechanisms. Azimuth-elevation is a common technique to boost up and catch solar energy. If an inappropriate setup is used in a solar power plant, the electrical power output subsequently falls off. Different approaches and methods are used to overcome the shadowing effect.

The vertical angle of solar panels is expressed by tilt or elevation angle. The angle parallel to the equator is the Azimuth angle, and the angle between the line drawn from the sun to the earth's center and the equator is known as the declination angle (δ). The angle that connects the solar radiation and boundary is the elevation angle as shown in Figure 1.4. The angle between the surface and the horizon is the inclination angle (β) and declares a positive value of β when the positive value is toward the equator for the cover. The angle that indicates the division of the vertical surface

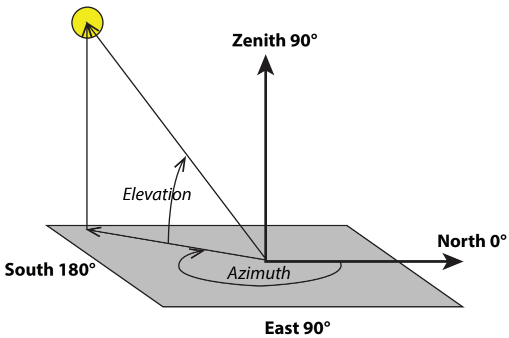

Figure 1.4 The azimuth-elevation angle.

from the local longitude is the surface azimuth angle (γ). The slant of the sun's beam regarding the clockwise direction on the north side is called the solar azimuth angle.

1.3.1 Steps of Evaluation of the Azimuth Angle

A new computational approach has been created for the MATLAB platform to implement numerical simulation. Two variant approaches (staggered array and square array) of layout configuration are optimized by simulation algorithm in the CPV field by gathering different parameters like the geographical and local annual meteorological data by assimilating frameworks including the local meteorological yearly detail, edge effect, land cost, etc. The new algorithm aimed to estimate the solar farm layout with a DAST in CPV.

The following step is carried out in this algorithm to estimate the azimuth angle:

1. Firstly, find the sun-tracking angles.
2. Estimate each side of the solar collector by coordinate transformation.
3. With the help of the ray/plane algorithm, reproduce the shadowing effect.
4. Investigate the annual energy generation.
5. Check out the LCOE of an energy plant.
6. To execute the iterative algorithm, the lowest LCOE is achieved by changing the corresponding orientation of the CSP system [18].

1.3.2 Sun-Tracking Angles

DAST mechanisms are necessary to find the highest amount of energy change in the CPV system and the path of sun's spot accurately in the daytime, in addition to direction change annually. Azimuth-elevation sun-tracking is a significant method for this purpose. The solar collector has three angles of orientation, which is zero. It is possible to derive the two sun-tracking angles of the azimuth-elevation sun-tracking method [19].

$$\alpha = sin - 1\delta sin\phi + cos\delta \, cos\,\acute{\omega}\, cos\phi \tag{1.1}$$

$$\beta = Cos - 1\left[\frac{sin\delta cos\phi - cos\delta cos\,\acute{\omega}\, sin\phi}{cos\,\alpha}\right] \tag{1.2}$$

- δ is the sun declination angle;
- ω is the hour angle;
- Φ is the latitude.

If sin ω is greater than zero, then the value of β will be 2π – β.

1.3.3 Coordinate Transformation

Each particular CPV system, such as the Fresnel lens, is modeled using a coordinate transformation approach. During the work, evaluate the shadowing effects among adjacent CPV systems and assess each CPV system's direction first. A 3-D coordinate system expresses CPV systems' immediate side during daily sun tracking operations. For the convenience of this 3-D coordinate transformation, create all transformations linear by adding a further dimension to space. The origin O (0,0,0) of global coordinate at the middle of CPs is expressed in Figure 1.5. The X, Y, and Z axes are all directed in the east, north, and zenith direction, respectively. The local coordinate indicates the starting point; at that point, the local origin, C(0,0,0), is found in the center of the framework rather than the CSP field.

The four edge points allocated to the four intersections of the system's structural frame serve as its representation. The position vector representing the edge points' coordinates in the coordinate system is set as follows:

$$P_k = [P_{kx}\, P_{ky}\, P_{kz1}] \tag{1.3}$$

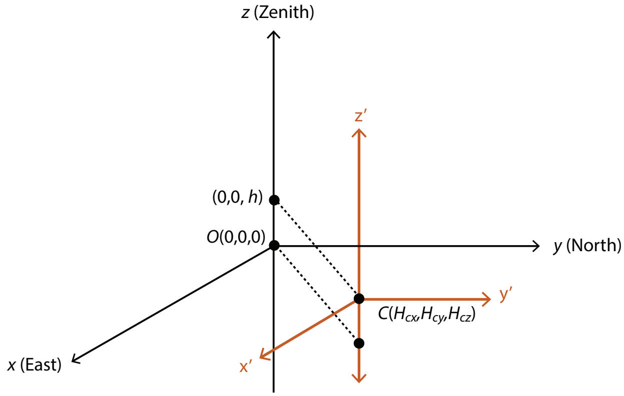

Figure 1.5 In the middle of CSP, the global coordinate system at O (0,0,0) and end of coordinates of frameworks is C (H_{cx}, H_{cy}, H_{cz}) after carrying out the coordinate function.

k = 1 indicates the uppermost left corner,

- K=2 is top right
- K=3 is lower right
- K=4 is lower left corner

After the coordinate transformation, the finishing coordinate of the edge point is expressed in matrix form, as exhibited in the following:

$$H_k = [H_{kx}\, H_{ky}\, H_{kz\,1}] \tag{1.4}$$

Changing the reference frame to a local coordinate system from a global coordinate by the processing of translational transformational matrix present regarding the center of solar panel system C (Hcx, Hcy, Hcz) can be written as

$$T_1 = [100H_{cx}\, 010H_{cy}\, 001H_{cz}\, 0001] \tag{1.5}$$

The final coordinate of the azimuth-elevation movement is produced by engaging the two rotational transformation matrices. The rotational transformation matrix is shown:;

$$[\alpha] = [100H_{cx}\, 0\cos\alpha - \sin\alpha\, H_{cy}\, 0\sin\alpha\, \cos\alpha\, H_{cz}\, 0001] \tag{1.6}$$