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Tilt and azimuth angles in solar energy applications – A review

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ABSTRACT

This paper presents a review of tilt angle and azimuth angles in solar energy applications. The paper involves an overview of design parameter, applications, simulations and mathematical techniques covering different usage application. The number of references analysing the tilt angle deployment in the context of the research papers of the different countries currently having operations in solar systems is much more significant. Different kinds of models and test methods of optimum tilt angle in different solar systems have been developed since 1956 which can be distinguished by their particular mathematical models or tracking techniques as shown in the latest researches. The mathematical models allows the calculation of different parameters of the solar radiation, the angle of inclination, and the optimum tilt angle of the collecting surface and the effects acting on the system.

1. Introduction

Concentrated solar power generation is considered one of the most promising renewable sources as the technologies are very close, in concept to conventional and traditional forms of power generation based on fossil-fuel combustion. Solar concentration is carried out in most of the solar systems by tracking the sun direction to focus the incident rays on a receiver, where a thermal process and generator unit is located to convert the solar energy into electric energy. This technology has many applications in relatively small, medium and large capacities. However, larger capacities are achieved by integrating small units to achieve solar collectors' farm. Currently, there are four main technologies that utilize the concentrated solar thermal energy which are (a) the parabolic trough systems, (b) the solar tower systems, (c) the Stirling solar dish systems and (d) the linear Fresnel systems. There are other applications to utilize the solar radiation in cooking or solar water heating. The researches discussed the best performance, design, simulation for the solar energy systems using optimum tilt angles [1–202]. There are number of studies and researches that were carried out in order to find the best performance of solar system areas around the world, and others in a comparison between different locations. There are numerous applications regarding the optimum tilt angle for a specific geographic location, as for example Photovoltaic systems [1–47], Solar Water Heater [48–55], solar cooker [56,57], solar still [58–63], solar powered thermoacoustic engines [64–67], building-integrated photovoltaic system (BIPV) [28,68–72], solar cooling [73], solar updraft tower power plant [74], and solar collectors [75–112], all of which are discussed in detail in this study.

A number of studies were carried out to find the optimum tilt angle and orientation (azimuth) of PV systems, solar collectors, or any other application in certain areas around the world, such as (Brisbane, Australia [3], Abu Dhabi, UAE [5], eight provinces of Turkey [8], Turkey [40], Izmir in Turkey [92,175,192], Athens, Greece [13], Greece [197], Madinah, Saudi Arabia [17], United States of America (USA) [21,188], Carbondale, Illinois, USA [189], North America [107], Canada [23], Taiwan [26], Sanliurfa, New Delhi, India [34], Egypt [39,104], Helwan, Egypt [141], Jordan [55], Iran [85,87], Basra, Iraq [103], Syria [89], 30 cities in China [93], Changsha, China [202], Malaysian territory [96], Perlis, Northern Malaysia [199], Kuala Lumpur, Johor Bharu, Ipoh, Kuching, Alor Setar in Malaysia [200], Kuala Lumpur, Malaysia [201], India [126], Dhaka, Bangladesh [127], South Africa [177,185], Japan [187], Cyprus [190], Burgos, Spain [191], Italy [193], Romania [194], Brunei Darussalam [195], Ghana [196], Singapore [198], the examples could continue and many more).

Abbreviation: ADHDEOA, AntDirection Hybrid Differential Evolution Algorithm; AI, Artificial Intelligence; ANN, Artificial Neural Network; BIPV, Building Integrated Photovoltaic System; CC, Compensation Chamber; CO_2, Carbon Dioxide; DFR, Diffuse Flat Reflector; DG, Diesel Generator; GA, Genetic Algorithm; GRNN, Generalized Regression Neural Networks; HDKR, Hay, Davies, Klucher, Reindl; LATITS, Large Angle Tilt Implantation of dopant Through Gate Sidewall Spacer; MAPV, Mirror Augmented Photovoltaic System;; PSO, Particle-Swarm Optimization; PSO—NTVE, Particle-Swarm Optimization Method with Nonlinear Time-Varying Evolution; PV, Photovoltaic; PVSYST, Photovoltaic Systems; RBFNN, A Radial Basis Function Neural Network; SNAOA, Sequential Neural-Network Approximation and Orthogonal Arrays; SPVEGS, Stand alone Photovoltaic Electricity Generation Systems; SUPP, Solar Updraft Tower power plant; SWH, Solar Water Heaters; TFT, Thin Film Transistor; TRNSYS, Transient System; UAE, United Arab Emirates; US, United States

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Nomenclature

G_T	The global irradiance, W/m^2
G_{B_t}	Total Beam solar radiation on a tilted surface, W/m^2
G_{D_t}	Total Diffuse solar radiation on a tilted surface, W/m^2
G_{R_t}	Total Ground-reflected solar radiation on a tilted surface, W/m^2
G_B	Beam radiation on a horizontal surface, W/m^2
G_{B_n}	Beam radiation in the direction of the rays, W/m^2
R_B	The beam radiation tilt factor
R_D	The diffuse radiation tilt factor
R_R	The ground-reflected radiation tilt factor

Greek symbols

β_{opt}	Optimum tilt angle, °
φ	Geographical latitude, °
δ	Declination angle, °
ω_{ss}	Sunset hour angle, °
β	Surface slope from the horizontal, °
ρ	Ground albedo

The techniques to optimize the tilt angle are shown in details where the most effective methods of maximizing solar radiation or energy collected on the surfaces, ANN, GA, SA and PSO techniques and all these techniques are shown by different optimum tilt angles equations such as Stanciu C. and Stanciu D. [78], $\beta_{opt} = \varphi - \delta$, Bakirci [8], $\beta_{opt} = 34.783 - 1.4317\delta - 0.0081\delta^2 + 0.0002\delta^3$, Rowlands et al. [23], $\beta_{opt} = \varphi$, Lave and Kleissl [21], $\beta_{opt} = \varphi - (1^o - 10^o)$, Moghadam et al. [87],$\beta_{opt} = 0.917\varphi \pm 0.321^o$, Benghanem [17], $\beta_{opt} = \varphi$, Ahmad and Tiwari [34] India in Summer is 13°, $\beta_{opt} = \varphi - 60^o$, And Winter is 47.5°, $\beta_{opt} = \varphi + 90^o$, Calabròa [31], $\beta_{opt} = \varphi - (26^o, 27^o, 28^o)$, Gunerhan and Hepbasli [92], In summer $\beta_{opt} = \varphi + 15^o$, In winter $\beta_{opt} = \varphi - 15^o$, Ulgen [175], for summer months is $\beta_{opt} = \varphi - 34^o$, and that for winter months is $\beta_{opt} = \varphi + 19^o$, Elminir et al. [141], $\beta_{opt} = \varphi \pm 15^o$, Duffie and Beckman [176], $\beta_{opt} = \varphi \pm 15^o$, Rusheng Tang and Tong [93], $\beta_{opt} = \varphi + (4^o \rightarrow -10^o)$, Gopinathan [177],$\beta_{opt} = \varphi$, El-Kassaby [104], $\beta_{opt} = \varphi + 3.5^o$, Lewis [178], $\beta_{opt} = \varphi \pm 8^o$, Garg [179], $\beta_{opt} = \varphi \pm 15^o$ or $\beta_{opt} = 0.9\varphi$, Duffie and Beckman [180], $\beta_{opt} = (\varphi + 15^o) \pm 15^o$, Lunde [181], $\beta_{opt} = \varphi \pm 15^o$ Kern and Harris [165], $\beta_{opt} = \varphi + 10^o$, Löf and Tybout [182], $\beta_{opt} = \varphi + (10^o \rightarrow 30^o)$, Yellott [183], $\beta_{opt} = \varphi + 20^o$, Heywood [184], $\beta_{opt} = \varphi - 10^o$, Chinnery [185], $\beta_{opt} = \varphi + 10^o$, Hottel [186], $\beta_{opt} = \varphi + 20^o$.

The main aim of this study is to review the current optimum tilt angles calculation methods to optimize the best design for the solar systems. The study takes into consideration the available solar potential, different techniques of solar tilt calculations, as well as all available analyses for different parts of the system. In Section 2, the use of solar tilt angles in different solar energy systems applications are described. The techniques of the solar radiation calculation are discussed in Section 3. In Section 4, the techniques to optimize the tilt angle and related equations are described. Finally, the conclusion is summarized in Section 5.

2. Tilt angles applications

This section presents an overview on most effective technologies and methods applied, in the latest researches, on the design parameters, applications, simulations and mathematical techniques of a tilt angle in different applications. The optimum design for any solar system will be achieved by the selection of the optimum components and materials, best analysis using simulation programs, mathematical techniques. The present research is focused on the effect of tilt angle on design. Many researchers discussed the optimum tilt angle, as showed in Tables (1–4) to achieve more efficient solar system designs using different techniques. This section will describe briefly these techniques in order to reach the most appropriate application for the system.

Most of the solar energy systems track the direction of the sun to focus the heat on the receiver, where a thermal process and generator unit is located or to collect the maximum solar radiation from the sun. This technology has many applications in relatively small, medium and large capacities. However, larger capacities are achieved by integrating small units to achieve solar collectors' farm. There are numerous applications regarding the optimum tilt angle for a specific geographic location, as for example Photovoltaic systems [1–47], Solar Water Heater [48–55], solar cooker [56,57], solar still [58–63], solar powered thermoacoustic engines [64–67], building-integrated photovoltaic system (BIPV) [28,68–72], solar cooling [73], solar updraft tower power plant [74], and solar collectors [75–112] these applications are discussed in details in this section.

Table (1) shows the current researches in the tilt angle covering different technologies used in Photovoltaic systems. Table (2) shows the current researches in the tilt angle covering the technologies used in solar water heaters, solar cookers, and solar still systems. Table (3) shows the current researches in the tilt angle used in solar powered thermoacoustic engines, building-integrated photovoltaic system (BIPV), solar cooling, and solar updraft tower power plant systems. Table (4) shows the current researches in the tilt angle in solar collectors systems.

2.1. Photovoltaic cells, modules, panels, and power plants

Photovoltaic system is one on the most promising applications in the solar energy field. Optimization of tilt angle is can to achieve the annual optimum tilt angle of the solar panels surface at a certain site or to achieve optimum tilt angle for PV modules to obtain maximum output power.

Hartner et al. [1] analyzed the wholesale market value of PV, potential fuel and CO_2 cost reductions through PV deployment under different tilt angles and orientations in 23 regions of Austria and Germany. Jeyaprabha and Selvakumar [2] described the optimal sizing of PV/battery/DG based hybrid system using optimal tilting of PV panel for remote locations using artificial intelligence (AI) techniques and without metrological data. Yan et al. [3] showed a theoretical model to estimate PV system performance with different tilt angles and orientations calculated in Brisbane, Australia, 26° N facing true North approximately. Ismail et al. [4] showed a hybrid power system from photovoltaic and microturbine at Palestine where optimization of PV tilt angle performed, which varies from 0° to 90° to maximize the annual energy production. Jafarkazemi and Saadabadi [5] obtained optimum tilt angle and orientation of solar cells panels and solar collectors in Abu Dhabi, United Arab Emirates (UAE). Based on the calculation results, the optimum is to change the tilt angle, at least twice a year. Yadav and Chandel [6] reviewed different optimization techniques and methods for determining optimum solar panel tilt angle at any site. Kaldellis et al. [7] investigated the optimum tilt angle in Athens, Greece. One of the PV panels at a fixed angle equals to the theoretical optimum angle and the other panel set to vary under standard angle step at a 15°, from 0° to 90°. Bakirci [8] optimized the tilt angles for the solar panels using solar radiation data measured to eight provinces in Turkey where the optimum tilt angle varies from 0° to 65° throughout the year. Lucio et al. [9] evaluated the optimum tilt angle using an algorithm for obtaining load minimum loss probability and optimum design of stand-alone photovoltaic systems in Europe. Asowata et al. [10] determined and validated the optimum tilt angles