UNIVERSITI PUTRA MALAYSIA

ESTIMATION OF GLOBAL SOLAR RADIATION ON INCLINED SURFACES

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By

SEYED ABBAS MOUSAVI MALEKI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Master of Science

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DEDICATION

I dedicate this thesis to my father, Seyed Hassan Mousavi Maleki, and to my late mother, Shahideh Maleki (PBUH), hoping this achievement will fulfil the dream that they had all those many years when they chose to give me the best education they could. Also I dedicate this thesis to my dear cousin, Dr. Mahdi Jafarlou, who has supported me like a brother.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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Chairman : Associate Professor Hashim Hizam,PhD
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Generally, in the weather stations, the global solar radiation is measured on horizontal surfaces. However, to maximize the amount of solar radiation incident on the collector surface, stationary solar convention systems, both solar photovoltaic and flat plat solar collectors, are mounted on inclined surfaces. It is not an easy task to measure global solar radiation on inclined surface, mainly due to the high price of measuring equipment and technique needed to do so.

Hourly global solar radiation on inclined surfaces can be estimated from global solar radiation on horizontal surfaces by several models. These models can be used to estimate components of hourly global solar radiation on horizontal (direct and diffuse radiation) and inclined surfaces (direct, diffuse and ground reflected radiation).

The main objective of this research was to recognize the most accurate model of estimating global solar radiation on inclined surfaces for Malaysia. In this research the hourly global solar radiation on horizontal surfaces was taken from a meteorological weather station in Universiti Putra Malaysia (UPM) for a year. To achieve this objective, the hourly global solar radiation on inclined surfaces was estimated by 126 combined models at three different angels. Moreover, hourly global solar radiation on inclined surfaces was measured at the same angles for a time from August 2014 to October 2015. The comparison between the estimated values and measured values was made based on three statistical methods. The values of monthly optimum tilt angle based on two accurate models were identifed and compared with that of the yearly tilt angle for a period of around 89 days, as recommended by previous researchers.

According to the results, the combination of Bugler model and Hawlader model was recognized as the most accurate model to estimate global solar radiation on inclined surfaces.The second best model was the combination of Temps-Clauson model and Hawlader model. The experimental results show the solar radiation incident on the proposed monthly tilt angles that was computed based on the first and second combinations of models were more than yearly tilt angle.

Abstrak tesis yang dikemukakan kedapa Senati Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

ANGGARAN RADIASI SOLAR GLOBAL PADA PERMUKAAN CONDONG

Oleh

SEYED ABBAS MOUSAVI MALEKI

Julai 2016

Pengerusi : Profesor Madya Hashim Hizam,PhD
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Secara umumnya di stesen cuaca, radiasi solar global diukur pada permukaan mendatar. Walaubagaimanapun, untuk memaksimumkan jumlah insiden solar radiasi ke atas permukaan pengumpul, sistem konvensyen solar tak bergerak, kedua-dua photovolta solar dan pengumpul solar plet rata dipasang pada permukaan condong. Ia bukan satu tugas yang mudah untuk mengukur radiasi solar global pada permukaan condong, terutamanya disebabkan oleh harga yang tinggi untuk peralatan mengukur dan teknik yang diperlukan untuk berbuat demikian.

Radiasi solar global setiap jam pada permukaan condong boleh dianggarkan daripada radiasi solar global pada permukaan mendatar dengan beberapa model. Model-model ini boleh digunakan untuk menganggarkan komponen radiasi solar global setiap jam pada permukaan mendatar (sinaran langsung dan meresap) dan condong (langsung, meresap dan radiasi pantulan tanah). Dalam kajian ini radiasi solar global setiap jam pada permukaan mendatar diambil dari stesen cuaca meteorologi di Universiti Putra Malaysia (UPM) selama setahun.

Objektif utama kajian ini adalah untuk mengenal pasti model yang paling tepat untuk menganggarkan radiasi solar global pada permukaan condong di Malaysia. Dalam kajian ini radiasi solar global setiap jam pada permukaan mendatar diambil dari stesen cuaca meteorologi di Universiti Putra Malaysia (UPM) selama setahun. Untuk mencapai objektif ini, radiasi solar global setiap jam pada permukaan condong telah dianggarkan menngunakan 126 model yang digabungkan pada tiga sudut yang berbeza. Selain itu, radiasi solar global setiap jam pada permukaan condong diukur pada sudut yang sama

dari Ogos 2014 hingga Oktober 2015. Perbandingan antara nilai yang dianggarkan dan nilai-nilai yang diukur itu dibuat berdasarkan tiga kaedah statistik. Nilai-nilai sudut kecondongan optimum bulanan berdasarkan dua model tepat telah dikenal pasti dan dibandingkan dengan sudut kecondongan tahunan untuk tempoh kira-kira 89 hari, seperti yang dicadangkan oleh penyelidik sebelumnya.

Berdasarkan kajian, gabungan model Bugler dan model Hawlader telah dikenalpasti sebagai model yang paling tepat untuk menganggarkan radiasi solar global ke atas permukaan condong. Model kedua terbaik adalah gabungan model Temps-Clauson dan model Hawlader. Keputusan eksperimen menunjukkan insiden sinaran solar pada sudut kecondongan bulanan yang dicadangkan yang dikira berdasarkan kombinasi pertama dan kedua model adalah lebih tinggi daripada sudut kecondongan tahunan.

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Finally, and most importantly, I would especially like to dear Fariba, she has been extremely supportive of me throughout this entire process and has made countless sacrifices to help me get to this point.

I certify that a Thesis Examination Committee has met on 25 July 2016 to conduct the final examination of Seyed Abbas Mousavi Maleki on his thesis entitled "Estimation of Global Solar Radiation on Inclined Surfaces" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee are as follows:

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LIST OF ABBREVIATIONS

I	Hourly global solar radiation on horizontal surface (w/m²)
I_b	Hourly direct beam solar radiation on horizontal surface (w/m²)
I_d	Hourly diffuse solar radiation on horizontal surface (w/m²)
I_o	Hourly extra-terrestrial solar radiation on horizontal surface (w/m²)
M_t	Hourly clearness index
I_β	Hourly global solar radiation on inclined surface (w/m²)
E_0	Eccentricity correction factor
$I_{b\beta}$	Hourly direct beam solar radiation on inclined surface (w/m²)
$I_{d\beta}$	Hourly diffuse solar radiation on inclined surface(w/m²)
I_r	Hourly ground reflected radiation on inclined surface (w/m²)
θ	angle of incidence for a surface facing the equator in degrees
θ_z	zenith angle
I_{sc}	Solar constan (w/m²)
x_i	ith measured value
$\bar{x}$	Measured mean value
y_i	ith predicted value
$\bar{y}$	Predicted mean value
$\bar{M}$	Average measured value of radiation power density on an inclined plane
RMSE	Root mean square error
MBE	Mean bias error
CC	Correlation Coefficient
ST	Local solar time
LT	Local standard time
L_s	Standard meridian for a local zone
L_L	Longitude of the location under study in degrees
P_1	Vicinity of the sun’s disc

P_2	Sky radiation from the region near the horizon.
Z	Correcting factor
m	Air mass

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter provides a general overview of the study that includes the background of the study, problem statement, followed by the research objectives and research questions. Also included are the scope and limitations of the study as well as the conceptual and operational definition of the key terms used in the thesis. To round up, an outline of the organization of the thesis is provided.

It is evidently clear that the development of technologies in recent times has given rise to the elevation of energy needs on a global scale. Consequently, the climate change, which is in turn induced by an increase in the emission of greenhouse gases (due to the combustion of fossil fuels), has been a major source of concern and a pressing challenge in the present world. Being among the natural and renewable sources of energy, solar energy has been considered as a viable alternative. Electricity can be produced from solar energy through using photovoltaic solar cells and concentrated solar power. It is important to note that the climatic conditions of a location have an impact on the solar radiation which is available on the surface of the Earth. Therefore, proper design of building energy systems, systems using solar energy, and also acceptable evaluations of the thermal setting inside buildings all necessarily require a knowledge of the local solar radiation. To do so, databases containing long-term measurements of data at the location of a given solar system have proven to be the best. However, limitations in covering of radiation measuring networks necessitate development of models for solar radiation. Having an estimate of normal solar radiation is significant for a large number of various solar applications. Nevertheless, it is not an easy task to collect such measurements, mainly due to the high price of measuring equipment and techniques needed to do so.

1.2 Problem Statement

Generally, in the weather stations, the global solar radiation is measured on horizontal surface, while maximum amount of solar radiation incident is measured on an inclined surface. The hourly global solar radiation on an inclined surface can be estimated by using hourly global solar radiation on a horizontal surface. During a good part of the last decade, various scholars have come up with models for prediction of solar radiation on inclined surfaces[Chandrasekaran and Kumar (1994), Erbs *et al* (1982), Hawlader (1984), Jacovides and Tymvios (2006), Karatasou, Santamouris, and Geros (2003), Lam and Li (2000), Louche, Poggi, Simonnot and Sanguinaires (1991), Miguel *et al* (2001), Orgill and Hollands (1977)]. These models have different scopes, ranging from being applicable to specific surfaces, requiring special measuring equipment, or being limited in scope. However, scientific engineering applications such as solar photovoltaic, thermal utilization, heat gain of buildings, energy simulation, and hourly values are generally needed. Moreover, lack of a comparison study of different methods applied on database obtained in Malaysia as well as finding the most accurate model for Malaysia to estimate solar radiation on an inclined surface have been the reasons behind conducting the present study.

1.3 Aims and Objectives

The main goal of this thesis is to find the best method to estimate solar radiation on inclined surface in Malaysia.

The specific objectives of the study are:

- To estimate hourly diffuse radiation and direct radiation on horizontal surfaces and estimate hourly diffuse, direct and reflected radiation on inclined surfaces.
- To compare the estimated hourly solar radiation on inclined surfaces with the measured hourly solar radiation on inclined surfaces by number of statistical analysis methods and identify the most accurate model to estimate hourly solar radiation on inclined surfaces in Malaysia.
- To identify the monthly optimum tilt angle based on the selected best models.

1.4 Scope and Limitations

Many meteorological stations around the world measure the global solar radiation on a horizontal surface. Regardless of this, there is also a small number of stations doing so on inclined surfaces. Few models are available for estimation of global solar radiation on inclined surfaces based on global solar radiation on horizontal surfaces. Finding the most accurate model for this study location is intended. To do this, the scope of this work includes:

- Installation of three ML-01 Si-sensor at three different angles (5°, 10° and15°) in an open area at Universiti Putra Malaysia (UPM).

- Collecting and monitoring of hourly global solar radiation data on three-mentioned inclined surfaces of PV site in the area under study (UPM), for over one year starting from August 2014 to October 2015.

1.5 Organization of the Thesis

The remainder of this thesis is organized in the following way: Overall, the thesis is presented in five chapters and organized as follows:

Chapter 1 provides a general overview concerning the estimation of hourly global solar radiation on an inclined surface from global solar radiation on horizontal data.

Chapter 2 contains an overview of the different works that have done to estimate solar radiation on an inclined surface. Instruments of measuring solar radiation and empirical methods for the estimation of radiation on an inclined plane are presented.

Chapter 3 deals with the main approach used in this research to achieve the objectives, and contains the different steps for designing the methodology. The first part is the numerical method of estimation of solar radiation on horizontal and inclined surfaces. The second part is dedicated to the experimental data. Components like pyranometer and data logger specifications are presented one after the other one. Finally, the last part serves to present the statistical methods.

Chapter 4 presents the results and analysis, including statistical test methods using SPSS version 22. The accurate models for estimation of global solar radiation on an inclined surface and the monthly optimum tilt angle calculated from accurate models are presented in this chapter.

Chapter 5 concludes the research presentation developed in this thesis with conclusions and several limitations drawn from the experiments. Finally, a range of potential research directions and suggestions for future works are outlined.

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