AN IMPROVED ALGORITHM FOR PHOTOVOLTAIC MODULE TEMPERATURE PREDICTION AND ITS TECHNO-ECONOMIC IMPACT ON ENERGY YIELD

MOHAMED A. M. ALMAKTAR

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Universiti Teknologi Malaysia

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Dedicated to

My mother Eswika Faraj and my wife Rawida Ali

My son Abdullah

&

Special dedication to

My beloved father Abdullah Almaktar who did not live to share my happiness and achievement.

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To ALLAH, the ONLY CREATOR to whom alone the grace, praises and appreciation return. {If you count the favors of Allah, you could not number them. Indeed, Allah is Forgiving and the Most Merciful} Verse: 18, Surat: The Bees-An Nahl. Numerous prayers, peace and blessings of Allah be upon our prophet, Muhammad and upon all his relatives and companions.

My beloved mother and father Eswika Farag and Abdullah Almaktar, my heart, my wife Dwaidi, and my eye, my son Bwaidi and not to forget my dear siblings, nephews and nieces. Engraving these names on my thesis is the least I can do to express my deep gratitude. Thank you so much for believing in me and always stay by my side no matter we are close or distant away. Your care, advices, concern, prayers and encouragement are unforgettable indeed.

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May Allah accept my effort and use me to serve His ummah and Islam.

ABSTRACT

Photovoltaic (PV) system comprising PV modules and related control system is the sole means through which the solar energy is converted directly into electricity. The PV module is generally rated according to its maximum DC power output (Wp) which is obtained under Standard Test Condition. However, this condition is seldom encountered, especially in the high temperature and variable irradiance climate like Malaysia. On the other hand, in the actual operating conditions, the energy generated from PV module is sturdily influenced by surrounding climate; hence, a performance evaluation model for PV system is necessary. This research proposes a mathematical algorithm to calculate the hourly, monthly and annually expected PV system energy output, considering the actual PV module temperature (Tm) increase effect. The new algorithm was developed due to the limitation in the existing methodologies particularly the one used in Malaysia by Malaysian Green Technology Corporation (MGTC). The developed Tm prediction model is based on the pre-processed hourly data measured for 9 months at the 92 kWp Building Integrated Photovoltaic (BIPV) GreenTech Malaysia, Bangi, Selangor which includes Tm, ambient temperature (Ta), solar irradiance (G), wind speed (Ws) and Relative Humidity (RH). The developed algorithm was compared to the model used by MGTC and validated with actual measurements. In addition, 5 years of hourly data for Ta, G, and Ws measured at 6 different locations in Malaysia obtained from Malaysia Meteorological Department were used for development of a solar radiation and energy output estimation models. The proposed energy model gives good result since it is closer to measured data compared to the PVWatts simulation tool. Results on the techno-economic analysis are also presented. The proposed energy output estimation model is expected to be useful for the PV system installer in the pre-installation phase in terms of feasibility and performance analysis of the PV system.

ABSTRAK

Sistem Photovoltaik (PV) terdiri daripada modul PV dan sistem kawalan adalah merupakan komponen penting penukaran tenaga suria ke tenaga elektrik. Modul PV biasanya diklasifikasikan mengikut kuasa keluaran maksimum DC (Wp) yang di uji di bawah Keadaan Ujian Standard. Walau bagaimanapun, keadaan ini jarang terjadi, terutamanya dengan suhu yang tinggi dan sinaran cahaya matahari yang berbeda-beda seperti Malaysia. Sebaliknya, dalam keadaan operasi yang sebenar, tenaga yang dijana daripada sistem PV adalah dipengaruhi oleh iklim persekitaran; oleh itu, satu model penilaian prestasi adalah perlu. Kajian ini mencadangkan satu algoritma untuk menganggar tenaga keluaran PV bagi setiap jam, setiap bulan dan setiap tahun dengan mengambil kira kesan peningkatan suhu modul PV sebenar. Satu algoritma baru telah dibangunkan disebabkan terdapat had dalam algoritma matematik sedia ada dan diguna pakai oleh Malaysia. Model ramalan suhu modul dibangunkan berdasarkan pra-proses data yang diukur setiap jam selama 9 bulan di 92 kWp Bangunan Photovoltaik Berintegrasi (BIPV) Green Tech Malaysia, Bangi, Selangor merangkumi suhu persekitaran (Ta), radiasi solar (G), kelajuan angin (Ws) dan kelembapan relatif (RH). Algoritma yang dibangunkan telah dibandingkan dengan model yang diguna pakai oleh MGTC dan disahkan dengan data sebenar. Di samping itu, data mateorologi bagi setiap jam untuk tempoh 5 tahun yang diukur di 6 lokasi berbeza di Malaysia yang diperolehi daripada Jabatan Meteorologi Malaysia telah digunakan untuk membangunkan model anggaran sinaran suria dan juga model pengeluaran tenaga. Model tenaga yang dicadangkan memberikan hasil yang baik kerana ia lebih hampir kepada data yang diukur berbanding dengan menggunakan model simulasi PVWatts. Keputusan analisis tekno-ekonomi juga dipersembahkan. Model anggaran tenaga pengeluaran yang dicadangkan dipercayai berguna untuk pemasangan sistem PV dalam fasa pra-pemasangan dan analisis prestasi sistem PV.

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LIST OF ABBREVIATIONS

AC	-	Alternating current
ANN	-	Artificial Neural Network
ANOVA	-	Analysis of Variance
ARY	-	Average Reference Year
a-Si	-	Amorphous silicon
BIPV	-	Building Integrated Photovoltaics
BOS	-	Balance of System
CdTe	-	Cadmium Telluride
CIS	-	Copper Indium Diselenide
CO_2	-	Carbon dioxide
COE	-	Cost of energy
DC	-	Direct current
EC	-	Energy Commission
EIA	-	Energy Information Administration
EPIA	-	European Photovoltaic Industry Association
FiT	-	Feed in Tariff
FFNNBP	-	Feed-forward neural network with back-propagation
GaAs	-	Gallium Arsenide
GCPV	-	Grid-connected Photovoltaics
GhGs	-	Greenhouse gases
GMDH	-	Group Method of Data Handling
GoM	-	Government of Malaysia
HOMER	-	Hybrid Optimization Model for Electric Renewable
IEA	-	International Energy Agency

JB	-	Johor Bahru
KeTTHA	-	Kementerian Tenaga, Teknologi Hijau & Air
KL	-	Kuala Lumpur
LCC	-	Life Cycle Cost
MLR	-	Multiple Linear Regression
O&M	-	Operation and Maintenance
MBE	-	Mean Bias Error
MBIPV	-	Malaysian Building Integrated Photovoltaic
MGTC	-	Malaysian Green Technology Corporation
MMD	-	Malaysia Meteorological Department
mono-Si	-	Mono-crystalline Silicon
MPE	-	Mean Percentage Error
MPPT	-	Maximum Power Point Tracking
NASA	-	National Aeronautics and Space Administration
NGO	-	Non-Government Organization
NOCT	-	Nominal Operating Cell Temperature
NPV	-	Net Present Value
NREL	-	National Renewable Energy Laboratory
NREPAP	-	National Renewable Energy Policy and Action Plan
PR	-	Performance Ratio
PSH	-	Peak Sun Hours
PTM	-	Pusat Tenaga Malaysia
PV	-	Photovoltaics
PVSMC	-	Photovoltaic System Monitoring Centre
RE	-	Renewable Energy
REPPA	-	Renewable Energy Power Purchase Agreement
RETScreen	-	Renewable-energy and Energy-efficient Technologies software
RH	-	Relative Humidity
RMSE	-	Root Mean Square Error
SEDA	-	Sustainable Energy Development Authority

SPSS	-	Statistical Product For Service Solutions
SREP	-	Small Renewable Energy Program
STC	-	Standard Test Conditions
TMY	-	Typical Meteorological Year
TNB	-	Tenaga Nasional Berhad
TRY	-	Test Reference Year
UiTM	-	Universiti Teknologi MARA
UNDP	-	United Nations Development Program
UTM	-	Universiti Teknologi Malaysia
ZEO	-	Zero Energy Office

LIST OF SYMBOLS

a	-	Diode ideality constant
α	-	Unknown regression coefficient representing the intercept
β	-	Unknown regression coefficient representing the slope
γ	-	Temperature coefficient of power
$^{\circ}C$	-	Degree Celsius
δ	-	Declination Angle
τ	-	Transmittance of glazing
ϕ	-	Latitude angle in degrees
η_{inv}	-	Inverter efficiency
η_{pvss}	-	Efficiency of the photovoltaic sub system
η_{pv-inv}	-	Efficiency due to voltage drop between PV system and inverter
%	-	Percentage
AM	-	Air Mass
C_{gen}	-	Cost of the PV array
C_{inst}	-	Cost of the installation (including supporting structures, wiring, protective elements, engineering etc.)
C_{inv}	-	Cost of the inverter
C_{sub}	-	The possible quantity of financial subsidy on the initial cost
c-Si	-	Crystalline Silicon
CO_2	-	Carbon dioxide
$\bar{d}$	-	Average i^{th} day of the month
e	-	Electric charge
$\in_{\text{i}}$	-	Random error for the *i*-th pair

E_{pv}	-	Average yearly energy output of the PV array
E_{pvaut}	-	The auto-consumed (not bought from the grid) annual energy generated by the PV system
E_{pvinj}	-	Annual energy generated from the PV system injected into the utility grid
K_i	-	Short -circuit current/temperature coefficient (*A/K*)
K_v	-	Open-circuit voltage/temperature coefficient (*V/K*)
f_{dirt}	-	The derating factor for dirt/soiling
f_{mm}	-	The derating factor for manufacturing tolerance
f_{temp}	-	The temperature derating factor
FF	-	Fill factor
G	-	Solar irradiance in W/m^2
GW	-	Gigawatt or 10^9 Watt
G_{STC}	-	Irradiance at STC (1000 Watt/m^2 or 1kW/m^2)
H	-	Peak sun hours (hours)
$\mathrm{H_0}$	-	Null hypothesis
H_0	-	Extra-terrestrial solar radiation
$\mathrm{H_1}$	-	Alternative hypothesis
hr	-	Hour
H_{tilt}	-	Annual total irradiation on the tilted plane (kWh/m^2/year or hours)
I_d	-	Shockley diode current
I_o	-	Reverse saturation or leakage current of the diode
I_{mp}	-	Maximum power current
I_{ph}	-	Photo current or current source
I_{sc}	-	Short-circuit current
I-V	-	Current - Voltage
J	-	Joule
k	-	Boltzman's constant ($1.3806503 \times 10^{-23} J/K$)
K	-	Kelvin

$\overline{K}_T$	-	Monthly clearness index
K_T	-	Daily clearness index
kWh/m^2	-	kilowatt hour per meter square
kWp	-	kilowatt peak
MW	-	Megawatt or 10^6 Watt
$\bar{n}$	-	Monthly mean daily number of hours of observed direct sunshine
N	-	Mean daily number of hours of daylight in a given month between sunrise and sunset
N_{par}	-	Parallel connections of PV modules
N_{ser}	-	Series connections of PV modules
P_{array}	-	The derated power produced from the PV array
q	-	Electronic charge ($1.60217646 \times 10^{-19} C$) in Coulomb
r	-	Pearson's correlation coefficient
R^2	-	Coefficient of determination
RM/kWp	-	Cost per kilowatt peak in RM
R_p	-	Parallel resistance represents leakage current of p-n junction
R_s	-	Series resistance
SS	-	Sum of squares
S_{xx}	-	Sum of product of variables x and x
S_{xy}	-	Sum of product of variables x and y
S_{yy}	-	Sum of product of variables y and y
T_a	-	Ambient temperature
T_c	-	Cell temperature
tCO_2/yr	-	million tons CO_2 per year
T_m	-	Module temperature
$T_{m.eff}$		The average daily effective module temperature, in degrees Celsius
V	-	Voltage
V_{mp}	-	Maximum power voltage

V_{oc}	-	Open circuit voltage
W_s	-	Wind speed
W/m^2	-	Watt per meter square

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CHAPTER 1

INTRODUCTION

1.1 Background

In the past three decades, the demand on electrical energy has been in gradual increase due to the industrialization evolution and population increase. The population of the world doubled from 3.2 billion in 1962 to 6.4 billion in 2005 and is forecasted to grow to 9.2 billion in 2050 [1]. In 1996, the world total electricity generation was about 13010 billion kilowatt-hours (kWh) and reached up to 18015 billion kWh in 2006 [2]. The US Department of Energy predicts the world energy consumption will rise 71% from 2007 levels by 2030 [3]. By 2040, according to the International Energy Agency (IEA) and the U.S. Energy Information Administration (EIA), the world-wide energy generation is predicted to be twice as high compared to 2007 records [4]. This means that a yearly increase by 2% thus doubling of the energy consumption every 35 years. Nevertheless, coal is still remaining the largest electrical energy source as it accounts for 37% of the total, followed by gas and oil [5]. Oil, gas and coal would continue, at least in the near future, to be the most predominant used fuels, making up about 80 percent of the total energy consumption in 2040 where the greatest portion goes to the industry sector with 53% and transportation with 27 % [6], refer to Figure 1.1.

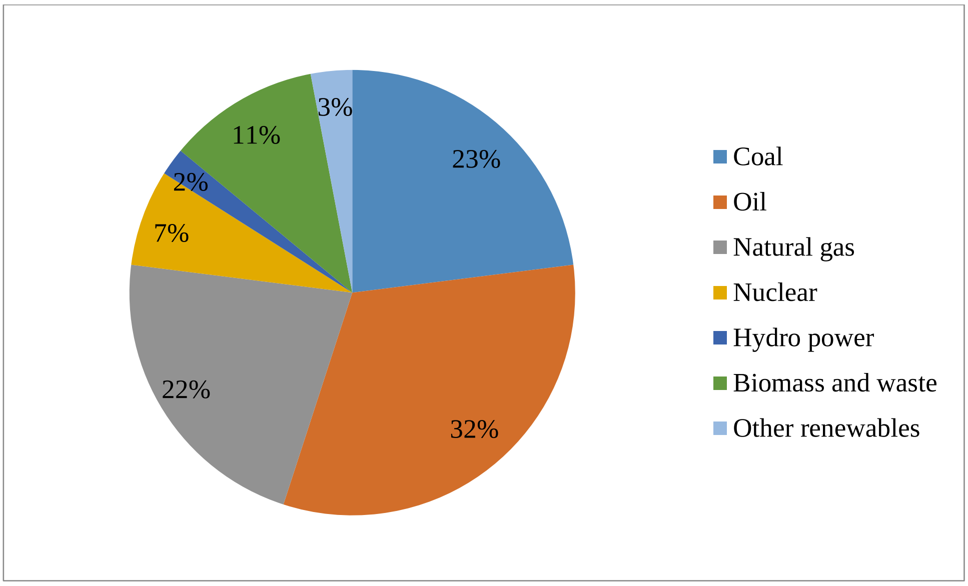

Figure 1.1 Energy sources share in energy demand [6]

On the other hand, oil prices were below US $20 per barrel prior to 2000 to nearly US $75 per barrel by the third quarter of 2006 and sudden reach up as much as $147 by mid-2008 [3]. At the end of 2010 the prices increased from about $82 per barrel to more than $112 per barrel in 2011, and at last quarter of 2014 the oil prices witnessed a shocking reduction to reach $74 per barrel by November [7]. However, it is expected that the oil price would be in ascending increase for the next three decades to reach up to $125 per barrel by the year 2035 [8], [9]. Hence, due to the liquid fuel fluctuating price besides its depletion over time [10], though currently they cover almost two third of electricity demand, has led to developed and developing countries making efforts in energy sources' diversification.

In addition, the global warming emissions resulting from energy production are a serious global environmental problem. Figure 1.2 explains the largest contributing source of greenhouse gas is the burning of fossil fuels which leads to the emission of carbon dioxide. The evidence comes from direct measurements of rising surface air temperatures and increases in average global sea levels, besides changes in many physical and biological systems [11]. For the above reasons, the world needs to expand energy supplies in a way that is secure, clean, affordable, and environmentally responsible.

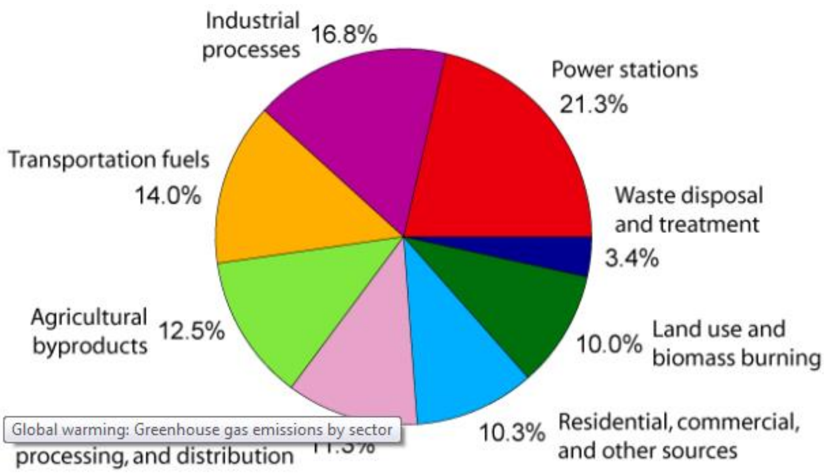

Figure 1.2 Annual greenhouse gas emissions by sector

Unlike fossil fuels, which are exhaustible, renewable energy (RE) comes from natural resources such as sunlight (main source of solar energy, wind, hydro and bioenergy), and geothermal heat, which are naturally replenished thus can be sustained indefinitely. Renewable energies ensure greater independence from energy imports, greater security of supply and strengthen the domestic economy. Globally, Germany renewable energies accounted for 12% of total final electricity consumption in 2013 and the goal laid down by German government is that the share of renewable energies in total gross electricity consumption will be increased to 30% and 60% by 2030 and 2050 respectively. In the United States, RE provided 9.3 percent, or 425 billion kWh of final energy share in 2012 [12]. According to forecasts made by the Chinese Electric Power Research Institute, RE installations will account for 30% of the total electric power installations in China by 2050 [13].

One of the promising RE sources is solar energy. Beside its free of cost, the sun radiates about 3.9 $\times 10^{26} W$ as a black body due to its high surface temperature with total energy delivered to earth~1018 kWh/year (8000x global energy consumption) [5], [14]. In Saudi Arabia, for example, the annual amount of solar energy that falls on its territory is estimated at about ten times the amount that is consumed in electrical energy [11]. Solar energy alone is projected to supply 30% of the world's energy demand by 2050 and to about 64% of the electricity supply in 2100 [15], as indicated in Figure 1.3. Approximately 15,000 MW, on a global basis, of new PV installations have been added during 2010, taking the entire PV capacity to almost 40,000 MW [16]. According to the International Energy Agency

Photovoltaic Power System Programme (IEA-PVPS) and European Photovoltaic Industry Association (EPIA) reports, the cumulative global PV capacity installed surpassed 100 GW by end 2012 [17], [18].

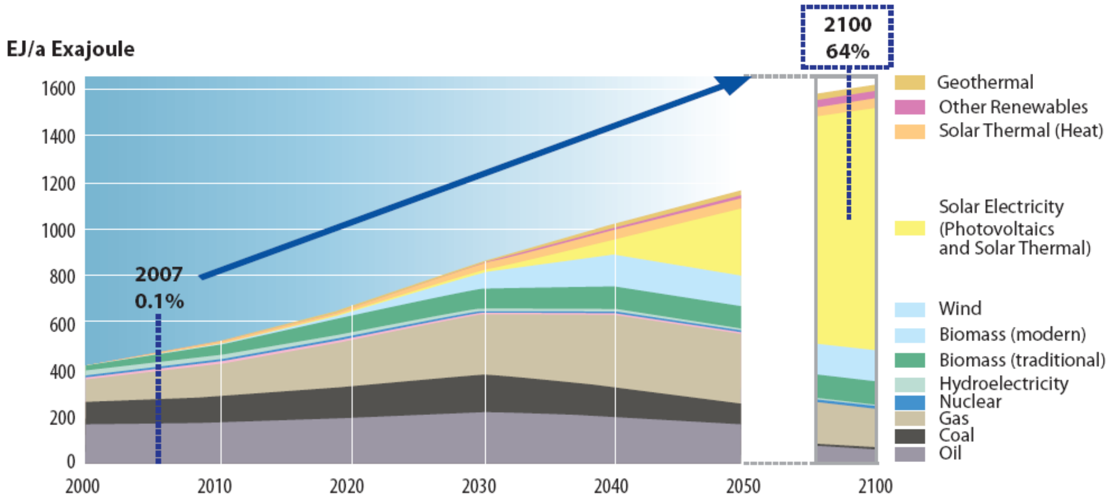

Figure 1.3 Global RE technologies development until 2100 [15]

The potential for solar power application in Malaysia is significant, given that Malaysia's averages solar-energy intensity level is 6 kWh/m2 per day on a horizontal surface [19]. The solar PV planning in Malaysia aimed for significant uptake, from merely 65 MW in 2015 to 18,700 MW in 2050, surpassing all other RE uptakes combined [20]. Grid-connected PV system (GCPV) in Malaysia will be the main market from 2015 onwards [15]. Malaysia targets 1250MW and 3100MW (25% of RE mix) solar power capacity to be connected to the grid by 2020 and 2030 respectively [21]. That is because PV system prices have declined due to progressive increase in conversion efficiencies and manufacturing economies besides governments' incentives, market competition and economies of scale [22].

As a result of government incentives, market competition and economies of scale, the average prices of photovoltaic cells shipped have declined steady over the past three years. For photovoltaic cells, the average price has decreased almost 11 %, from US $1.27 in 2009 to US $1.13 in 2010, and the average price of photovoltaic modules per Wp fell nearly 30 %, from highs of US $3.5 in 2008 to lows approaching US $2.79 in 2009 to US $1.96 in 2010 [3]. Industry analysts predict the costs associated with development of large-scale solar power plants will reduce by half by 2020. This has led to that by today costs are 10-20 cents a kWh to produce electricity from solar cells [23].

Demand for silicon material is expected to increase from 120,000 tonnes in 2010 to 400,000 tonnes in 2015. In 2005, global solar markets reached US$ 11.8 billion, 55% up than 2004 [1]. The production of solar cells has grown at an average annual rate of 37% in the past decade, i.e. from 77.6 MWp in 1995 to 1817.7 MWp in 2005, and at an average annual rate of 45% in years between 2000 and 2005 (from 287.7 MWp to 1817.7 MWp). In 2010, the PV industry had witnessed an astonishing increase of global cell production to reach up to 27.2 GW—as much as the output of the years 2005-2009 combined. This was an increase of 118% over the 12.5 GW produced in 2009 [24].

1.2 PV Technology

Despite its high capital cost comparing to other conventional sources of power, PV is extremely modular, easy and fast to install and accessible to the general public. Furthermore, the PV systems are static, quite, and free of moving parts, thus require little operation and maintenance costs. PV cell or module is the key component comprising the PV system, and is the sole means whereby the solar energy is converted into electricity. It is well known that for different PV technologies, having different seasonal patterns behavior. These differences are due to the variations in spectral response, the different temperature coefficients of voltage and current. Basically, the PV cell is made of a semiconductor material. These semiconductor technologies include; crystalline silicon, which is the most popular where its market share is 80%-90%, thin film solar cells, and third-generation PV technology [25]. The crystalline silicon can be categorized to single (monocrystalline) and multi- crystalline. The thin films include amorphous silicon (non-crystalline), and polycrystalline materials such as: Selenium, Silicon Carbide, Cadmium Telluride, Indium Gallium Arsenide Nitride, Copper Indium Diselenide (CIS), and Copper Indium Gallium Selenide (CIGS). The third-generation PV technologies include; concentrating PV (CPV), dye-sensitized solar cells (DSSC), and organic solar cells [23].

Silicon constitutes about 26% of the Earth's crust and is the second most abundant element in weight, oxygen being the largest [26]. Though Crystalline Silicon (c-Si) modules will continue to dominate the market, its share of the PV market has been gradually eroding due to competition from the cheaper industry, thin films. 2013 had witnessed an increase in the market share for Thin Film to 25%, where the demand for thin film modules increased from 100 MWp in 2005 to 1,000 MWp by 2010 increasing its share of the module market from 6% in 2005 to 20% by 2010 [16]. Although it has a lower efficiency, the advantage of thin films is its potential to produce PV modules at costs much lower than c-Si cell modules. Also, experiments from National Renewable Energy Laboratory (NREL) proved that thin films modules (specifically CIS) performs better at low irradiance level and produces more power when its temperature is higher compared to other PV technologies [27].

At present, the main PV-powered applications include communication and signaling, special commercial and industrial applications, solar street, traffic signals, garden and lawn lamps, calculators and solar toys, off-grid PV systems such as water pumping, safety and protection devices, consumer use, and generally at locations without the presence of the utility grid. GCPV, on the other hand, can play a vital role in lowering electricity demand and shifting peak load.

Most stand-alone PV systems are used in remote areas, where either the connection to the grid is invisible or would be too costly [28]. The main difference between the two types is the existence of the storage battery in the stand alone PV system, as the name implies which indicates the 100% reliance on the PV system.

Connecting the PV to the grid has brought many benefits to the electricity utility planners as well as to utility operators. Some of such advantages are relieving the transmission and distribution networks, lowering the peak demand and furthermore postponing the investment cost of upgrading the network due to gradual increasing of demand.

In designing power generation system that integrates PV there is a basic requirement to accurately estimate the output from the proposed PV array under operating conditions. Good system design is indispensable to provide reliable installed system. An appropriate sized PV array enables consumers, particularly of remote area systems, to receive a reliable predictable energy supply at reasonable cost.

For an optimum design of the PV power systems, it is desirable to measure their long-term performances at the site of installation. Therefore, an accurate evaluation tool for PV system performance is vital for the PV system component manufacturers, research and development teams, systems integrators and end customers. Such reliable tool is critical for the continuing development of the PV industry and also key metric in helping to identify future needs [29].

1.3 PV System Design and Performance

There are several methods and softwares available for sizing and estimating the performance of PV system. One basic method uses average monthly meteorological data to estimate the energy yield. Simplified algorithms for PV energy systems predict the long-term performance by eliminating the use of hour-by-hour simulation procedure and instead it is done by means of mathematical models [28]. The basic requirement is the solar irradiation potential for the specified location over a period of time, the load demand and some model parameters as input. In [30] based on the daily utilizability function, monthly average energy to be delivered to the load/ to be stored/ to be dumped is estimated from array parameters and monthly average meteorological data.

A more complex method requires detailed inputs and employs time series simulations over an entire year to predict the energy yield. There are commercially available designing tools for PV technology applications such as the Renewable Energy Technology simulation tool (RETScreen) [31], Hybrid Optimization Model for Electric Renewable (HOMER) [32], and PVsyst software [33]. Using the aforementioned simulation tools, the user have to specify the location, type of installation (i.e., stand alone or GCPV) and size of components. However, all such available tools share the feature of using the average monthly solar radiation from National Aeronautics and Space Administration (NASA). In [34] it was reported that there is a great variety of sizing tools for PV standalone systems since they use different assumptions to calculate radiation on tilted surfaces and different modeling of PV system components; therefore, lead to significantly different results when sizing the same standalone PV system. It was also investigated that there is sometimes a difference of more than 70% in the array sizing when comparing design methods and results using software tools. Obviously, this hinders the adoption of rigorous sizing procedures among PV engineering practices and PV professionals.

There are several studies in literature focusing on performance of PV systems at specific locations since some regions have different characteristics and privacy than other locations. In general, there are few works in literature evaluating the performance of PV system in Malaysia and in tropics. In [35], a field operation evaluation for 5 kWp GCPV system to assess the productivity of the system was conducted. It was found that the average PV performance ratio is 73.12% and the daily yield factor of the PV system is 2.51kWh/kWp/day. However, it was concluded that the productivity of the system is below the prospected rate. This is interpreted as either the system has a connection or inverter problem, or the energy output estimation tool used has a lack of accuracy. In [36], utilizing real data obtained from Malaysia Meteorological Department (MMD), the Adaptive Neuro-Fuzzy Inference Systems (ANFIS) technique was used to estimate the energy output and optimize the sizing of hybrid PV/wind/battery system. However, the developed model has not been tested on real installed systems even though led to accurate results compared to HOMER software. A mathematical optimal sizing model of a standalone PV system applied for Malaysia weather conditions has been presented in [37]. Based on the load demand, solar radiation and ambient temperature of the site selected, the PV array output and the battery size were estimated.

In Malaysia, the Australia/New Zealand Standard (AS/NZS 4509.2-2002) system design [38] has been used by Malaysia Green Technology Corporation (MGTC), formerly known as Pusat Tenaga Malaysia (PTM), to calculate the annual expected energy output of a PV system [39]. The Standard uses the day-average maximum ambient temperature and annual peak sun hours as input data. However, averaging the daily ambient temperatures between the minimum and highest degrees over a course of a day, though the ambient temperature fluctuations are non-linear, affects the PV energy output calculation.

As for the PV module, Watt peak (Wp) is provided under standard test conditions (STC) of 1000 W/m2 irradiance level, Air Mass (AM) of 1.5 and 25ºC PV cell temperature. Yet these conditions do not represent what is typically experienced under actual operating conditions where less irradiance level and higher module temperature will reduce the energy output and overall system performance.

For these reasons, there is a need to identify suitable PV modules and an accurate energy estimation model that suits Malaysia's weather conditions. With the accurate simulation tool, the optimum power output from the photovoltaic generator can be achieved, and the mismatch can be minimized. This research undertakes the task of predicting the energy output of a PV system utilizing real historical hourly records of meteorological parameters. PV module temperature estimation model has been developed to take into consideration the derate factor of PV module temperature effect.

1.4 Problem Statement

In designing a power generation system that incorporates PV there is a basic requirement to accurately estimate the output from the proposed PV array under operating conditions. That is because an accurate estimation of PV system energy output has a direct effect on PV system sizing such that avoiding under/over sizing of the system. This in turn has a reflection on PV system investment cost. In other words, an appropriate sized PV array enables consumers to receive a reliable energy supply at reasonable cost. The studies on photovoltaic performance and economic evaluation for the photovoltaic system under actual Malaysia condition have some limitations. The limitations are the use of monthly average solar irradiance from NASA which does not consider the variation of the solar irradiance over the course of the day, and also the calculation of the PV module temperature from maximum day-average ambient temperature. This research focuses on overcoming such limitations and contributing to improve the methodology used to estimate the PV system energy output in Malaysia.

Two main problems are identified in the PS which are the focus of this research: 1- using the real hourly data of solar radiation which is unlike the methodology used in Malaysia and 2- calculating the PV module temperature hourly by the proposed model. The proposed model overcome the conventional calculations that calculates the PV module temperature on average monthly basis..

1.5 Significance of the Research

- The study shall benefit the issue of optimal design and sizing of solar photovoltaic installations in Malaysia by accurately estimating the potential of energy output of PV system.
- The developed PV energy output estimation model is generalized. With the availability of the meteorological data for any geographic location worldwide, the model can provide pre-visibility study about any system capacity intended to be installed at the site.
- The study shall come out with generalized models for estimating the solar irradiance and module temperature in Malaysia. i.e., it can be used to estimate the solar irradiance and module temperature at any location within the country if that particular site has available meteorological data such as the ambient temperature, wind speed, and humidity.
- The accurate estimation of PV module temperature shall also help in PV system performance studies and economic analysis before the prior to system installation.
- The study is envisaged to contribute towards more efficient PV systems particularly for home applications i.e., roof top or building integrated. As the technology matures the PV system cost is coming down enabling the electricity price from PV technology reaches the grid parity.

1.6 Research Objectives

The objectives of this research are as follows:

i. To analyze and model the performance of PV module under actual operating conditions.
ii. To improve the mathematical algorithm of MGTC that estimates the energy yield of GCPV system in tropic climate of Malaysia. This can be achieved by accurately estimating the BIPV module temperature taking into account various meteorological factors.
iii. To analyze solar irradiance data obtained from Malaysia meteorological Department for some sites in Peninsular Malaysia and comparing them with NASA database.
iv. To model the hourly solar irradiance in Malaysia.
v. To validate the proposed Tm, G, and energy output calculation models using actual data and PVWatts simulation software.

1.7 Research Scope

The main scope of this research is the accurate estimation of energy output of PV system in Malaysia. It is focused on residential applications specifically the GCPV, whether it is rooftop or building integrated PV systems.

It is demonstrated in the literature that for each 1 $^{\circ}C$ increase in PV module temperature is approximately 0.3-0.5% decrease in its efficiency [40], [41]. Thus for the optimum design of PV power systems it is desirable to measure their long term performances at the site of installation. Therefore, this research shall develop a mathematical model to accurately estimating the energy output of PV system. In this model, the PV module temperature would be estimated "hourly" considering various climatological factors such as relative humidity which can reach up to 100% in Malaysia, and also wind speed. The other important factor affecting the accurate estimation of PV energy output is the solar irradiance at a specific location.

Therefore, for optimal design of PV system, the research utilizes hourly measured data for the solar irradiance measured at six different locations in Malaysia rather than importing the solar radiation data from NASA. For other locations in Malaysia, the research would contribute developing a mathematical model for predicting the global solar irradiance in any region within Malaysia. These can be accomplished by analyzing the real data obtained from Malaysian Meteorological Department and Malaysian Green Technology Corporation. Data include: solar irradiance, ambient temperature, actual module temperature, wind speed, and relative humidity. Also, data for actual energy output of real PV systems having different capacities and also located at different geographic locations are analyzed.

The mismatch of the energy production under real practical situation or system under operating condition, taking into account local geographical conditions is the focus of this research. The PVWatts simulation tool investigated in this research uses monthly average solar radiation and ambient temperature data to estimate the PV module temperature and the energy produced. Since the PVWatts and similar available commercial softwares utilize data from NASA which are taken from satellite not from real measurements, this research investigates the database from NASA for some meteorological parameters and historical database taken from real records for different locations in Peninsular Malaysia. Therefore, preliminary or prefeasibility evaluation on PV system sizing is significantly important to give acceptable result and valuable information to the PV system designer and installer.

1.8 Research Methodology

This research investigates the energy output of the installed photovoltaic systems using three different technologies, polycrystalline, monocrystalline, and amorphous silicon.

The flowchart presented in Figure 1.4 covers all the issues of the approach towards the completion of the project.

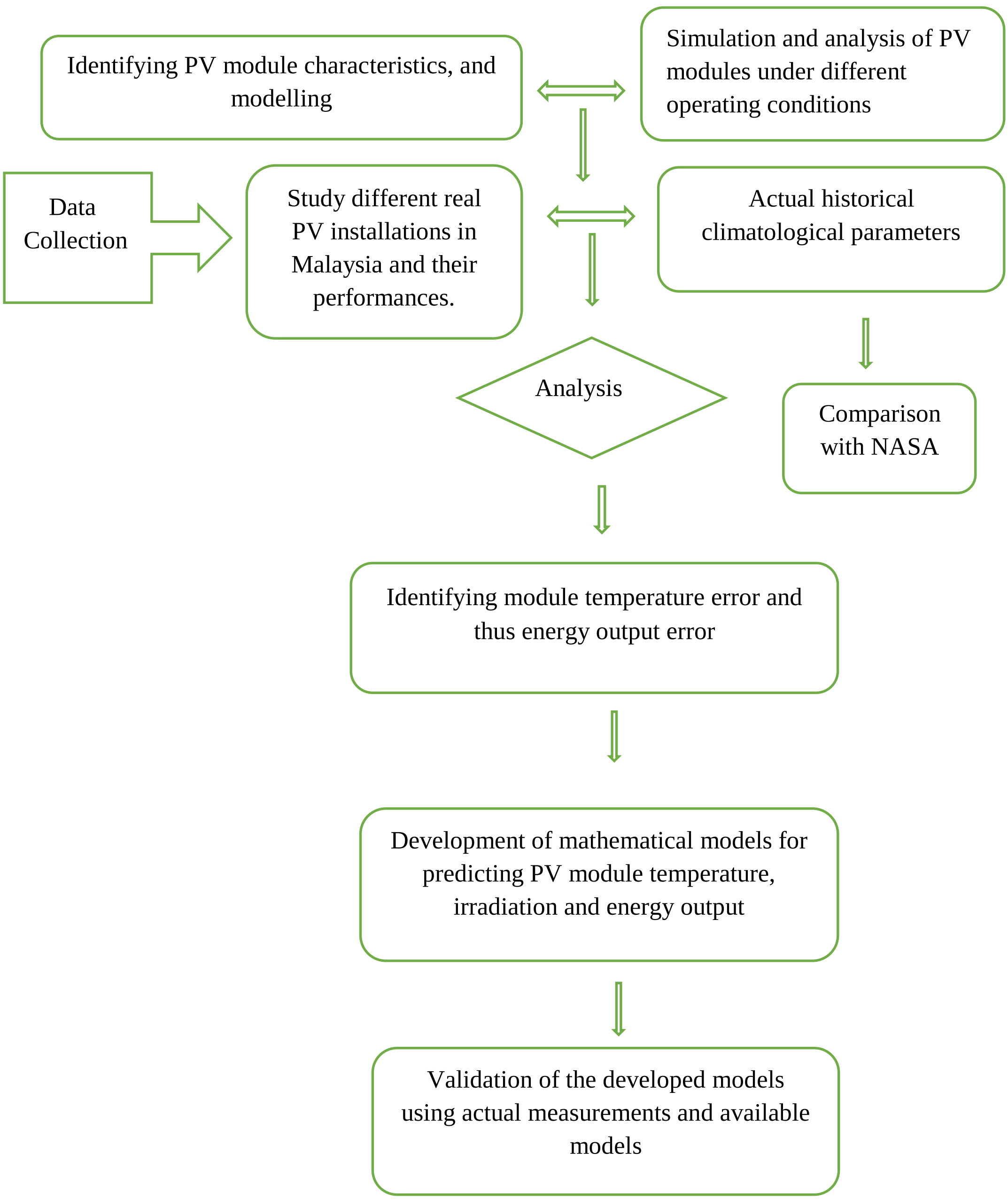

Figure 1.4 Research methodology

The research starts with the study of PV module characteristics. The PV circuit is then modeled in order to simulate, analyze, and evaluate the PV module under different operating conditions. Data of actual historical climatological parameters from MMD and also actual PV system performance from MGTC are collected. Analysis of the obtained actual measured energy output of PV installations and the historical meteorological parameters, by comparing them to data provided by NASA, is then conducted. Accordingly, the module temperature discrepancy and thus energy output error between MGTC calculations and the actual measurements are identified. As a result, a mathematical model using regression analysis and other tools such as Artificial Neural Network (ANN) and Group Method of Data Handling (GMDH) methods, that can estimate the module temperature, solar radiation and its energy output for Malaysia weather condition, are developed. Finally, the developed models are validated using actual measurements and available models and softwares such as PVWatts.

1.9 Thesis Outline

This thesis consists of six chapters organized as follows:

Chapter 1 provides a brief introduction of the research work. It covers topics on problem identification, importance of research, research objectives, research scope, research methodology and thesis outline.

Chapter 2 presents the photovoltaic generation technology. This chapter reviews the basic characteristics of a photovoltaic cell and its modeling. Types of PV systems are also presented. Then the chapter discusses the solar energy or specifically the solar photovoltaic development outlook in Malaysia; the massive potential of solar energy in the country, the key players in the solar energy development and the early solar energy policies and programs in the country, followed by an explanation on the Feed in Tariff (FiT) recently introduced in the country to encourage solar PV development. Finally, results of PV module and system characteristics are included in this chapter.

Chapter 3 reviews the estimation models of PV module temperature. Modeling of solar radiation is also reviewed. The Malaysia standard for calculation of PV system energy output is presented, discussed and evaluated. The PVWatts simulation tool which is the benchmark of the developed energy output simulation model is briefly presented.

Chapter 4 presents the proposed photovoltaic system performance model. This chapter discusses the factors which influence the PV system outputs by first introducing the proposed PV module temperature prediction model. Two proposed model are presented, the ANN based model, and another mathematical model based on regression analysis using SPSS software. A proposed model for predicting the global solar radiation in Malaysia is also presented in this chapter. And finally, a proposed energy output estimation model for PV system installed in Malaysia is presented.

Chapter 5 presents the meteorological data analysis and validation of data obtained from Malaysia Meteorological Department with NASA. Results of the new PV module temperature prediction mathematical model which satisfies all the statistical indicators were determined, discussed and validated. Results of the ANN model was also included and compared with actual measurements. Results of the proposed solar radiation model using multi-regression analysis and GMDH method were presented and validated. The development of energy output estimation simulation model which was calculated on hourly, monthly and annual basis is explained and compared with the PVWatts software tool and also validated with real PV systems having different capacities and technologies and also geographic locations.

Chapter 6 deals with an economic analysis of PV system installations. The model of the Net Present Value and the Pay-Back Period, which are common parameters used to determine the profitability of a project in the economics and finance, are presented. Economic analysis results of the 9kWp GC PV Systems at UTM Johor Bahru, are discussed. Using Homer simulation software, sensitivity economic and environmental analysis of the 9 kWp UTM solar home are also provided.

Finally, the overall conclusions of the study and recommendations for future works in the field of home applications photovoltaic system are outlined and presented in chapter 7.

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