UNIVERSITI PUTRA MALAYSIA

TECHNICAL LIMITATIONS OF LARGE-SCALE GRID-CONNECTED PHOTOVOLTAIC POWER PLANTS IN PENINSULAR MALAYSIA

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By

SABO MAHMOUD LURWAN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

To my Parents, my family, particularly ALHAJI DANLADI HARUNA, and my brother Abdul Danladi Haruna.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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February 2017

Chairman : Norman Mariun, PhD, PEng
Faculty : Engineering

Deployment of large-scale grid-connected PVs power plants requires very reliable technical evaluation to reduce electricity demand and achieve efficient utilization of electricity generated from PV. At lower PV penetration levels, it is likely that the energy mix could be under-supply utility demand, thus requiring extra units of generators, while at higher penetration levels it may oversupply demands, thus wasting generator capacity. Therefore, determining the optimum installed capacity, technical limits, and economic benefits of large-scale PV systems are the main issue for both power utilities and decision makers. Although previous studies have attempted to evaluate large-scale PV integration into the existing grid systems, the most critical limitation in these studies, which are mainly based on physical models and technical parameters (voltage and current) through simulations, is the lack of connection to spatial planning activities. Concisely, energy prediction tools and models are mostly detached from the real world (from a geographic perspective) as they generally account only for topological relations within the system, neglecting the actual topography and spatial relationships. In addition, none of these studies have incorporated the topographical, topological features and geographic information systems (GIS) to assess the technical limits of large-scale PV implementation. Thus, integrating the geographic nature of renewable energy resources (PV), accounting not only for energy-related variables but also for spatial variables, is a perennial challenge. This study describes the development and validation of an alternative method (named as the generation-demand matching model GDMM) for evaluating the large-scale implementation of grid-connected PV power plants in Peninsular Malaysia relative to its interface with the traditional power grid system. The method which composed of the optimal site, electricity generation, and electricity demand explicitly provides a detailed assessment of the temporal and spatial factors that facilitate the match between PV generated electricity and electricity demand. These evaluation factors are analyzed using simulations of PV electricity generation located at optimal sites performed using a proposed optimal site based PV performance model (PVOBM). Optimal sites along with physical constraints were mapped using a proposed optimal

site definition model (ODM) combined with geographic information systems (GIS) for visualization and representation by location. PV electricity generation at different levels of penetration was predicted hourly for a year using time series analysis. This allowed comparison of electricity generation with electricity demand to evaluate the impacts of increasing levels of PV penetration, economy and emission reduction. A novel feature of the proposed method is its combination of topographical and topological map data with metric data. The ability of the new method to accurately predict the performance of PV compared to PVWatts demonstrates the robustness of the method in evaluating the technical limits of PV systems in conventional power systems.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

HAD TEKNIKAL LOJI JANA KUASA GRID SAMBUNGAN FOTOVOLTAIK BERSKALA BESAR DI SEMENANJUNG MALAYSIA

Oleh

SABO MAHMOUD LURWAN

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Penggunaan loji janakuasa grid sambungan fotovoltaik (PV) berskala besar memerlukan penilaian teknikal yang sangat tinggi bagi mengurangkan permintaan kuasa elektrik dan mencapai kecekapan penggunaan tenaga elektrik yang dijana oleh PV. Pada tahap penembusan PV paling rendah, berkemungkinan campuran tenaga tidak dapat memenuhi permintaan utiliti, maka ia memerlukan penambahan unit penjana, namun ketika tahap penembusan tinggi pula ia menyebabkan lebihan bekalan permintaan, dengan itu kapasiti penjana terbazir. Oleh itu, penentuan kapasiti pemasangan optimum, had teknikal dan manfaat ekonomi bagi sistem PV berskala besar merupakan isu utama bagi kedua-dua utilit-utiliti kuasa dan pembuat keputusan. Walaupun kajian-kajian sebelum ini telah cuba menilai integrasi PV berskala besar ke dalam sistem grid, had yang paling kritikal dalam kajian ini; yang mana sebahagian besarnya berasaskan kepada model fizikal dan parameter teknikal (voltan dan arus) melalui simulasi, adalah kekurangan sambungan kepada aktiviti perancangan lokasi. Secara ringkasnya, alatan dan model-model ramalan tenaga kebanyakannya tersasar daripada dunia realiti (dari perspektif geografi) kerana secara umumnya akaun hanya untuk hubungan topologi dalam sistem sahaja, dan mengabaikan topografi sebenar dan lokasi. Disamping itu juga, tiada satu pun daripada kajian-kajian ini menggabungkan topografi, ciri-ciri topografi dan sistem maklumat geografi (GIS) untuk menilai had teknikal pelaksanaan PV berskala besar. Maka, pengintegrasian sifat geografi sumber tenaga boleh diperbaharui (PV), menyumbang bukan sahaja kepada pembolehubah yang berkaitan dengan tenaga tetapi juga lokasi tersebut merupakan cabaran utama. Kajian ini menerangkan tentang pembangunan dan pengesahan kaedah alternatif (dikenali sebagai model kesepadanan permintaan penjanaan, GDMM) untuk menilai pelaksanaan loji janakuasa grid sambungan PV berskala besar di Semenanjung Malaysia berbanding dengan sistem grid kuasa tradisional. Kaedah ini terdiri daripada tapak optimum, penjanaan elektrik, dan permintaan elektrik, nyata memberikan penilaian terperinci secara sementara dan faktor lokasi bagi memudahkan sepadanan antara penjana elektrik PV dan permintaan kuasa elektrik. Faktor-faktor penilaian dianalisis menggunakan simulasi penjana

elektrik PV yang diletakkan di tapak optimum, dilaksanakan menggunakan tapak optimum yang dicadangkan berasaskan kepada model prestasi PV (PVOBM). Tapak optimum dipetakan bersama kekangan fizikal dengan menggunakan model tapak definisi optimum (ODM) yang telah dicadangkan digabungkan bersama sistem informasi geografi (GIS) untuk visualisasi dan gambaran mengikut lokasi. Penjanaan elektrik PV pada setiap tahap penembusan yang berbeza telah diramal setiap jam selama setahun menggunakan analisis siri masa. Hal ini, menerbitkan perbandingan antara penjanaan elektrik dan permintaan elektrik untuk menilai kesan peningkatan tahap penembusan PV, ekonomi, dan pengurangan pelepasan CO_2. Suatu ciri pembaharuan oleh kaedah yang dicadangkan adalah kombinasi data peta topografi dan topologi bersama data metrik. Keupayaan kaedah baru ini adalah untuk meramal dengan lebih tepat prestasi PV berbanding dengan PV Watts dan menunjukkan keteguhan kaedah tersebut dalam menilai had teknikal sistem PV dalam sistem kuasa konvensional.

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This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered too.

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A_{bb}	Annuity value of buyback payments
$A_{elecsav}$	Annuity value of electricity savings
A_{fuel}	Annuity cost of fuel
$A_{O\&M}$	Annuity cost of operation and maintenance
Asr	Annual solar radiation
$AtoP$	Annuity to present value conversion factor
$BBRate$	Buyback rate
C_i	Cost of inverter
$Cred_{state}$	State investment incentive percentage credit
$Cred_{fed}$	Federal investment incentive percentage credit
CS	Cost savings from emission reduction
CRF	Capital recovery factor
C_s	Installed cost of the system
d	Discount rate
d_n	Nominal discount rate
d_r	Real discount rate
$ElecRate$	Electricity rate
Em_i	Total mass emission from all sources for year I without PV
Em_{iPV}	Total mass emission with PV installed
Em_p^n	Emission rate for a unit of energy production with fuel type n
EP_i	energy generation without PV in year i
$ElecRate_{nbb}$	Retail electricity rate at the end of buyback contract period
Er_i	Emission reduction
F	Future value
FF	Flexibility factor
$F_{i,k}$	Future value of inverter replacement
$FtoP$	Future value to present value conversion factor
g_e	Annual growth rate in electricity rate
g_i	Annual growth rate in inverter cost
$g_{i,n}$	Nominal growth rate in inverter cost
$g_{i,r}$	Real growth rate in inverter cost
g_{nm}	Annual growth rate in value from net metering

i_g	Inflation rate
IC	Installed capacity
n	lifespan
n_{bb}	Length of buyback agreement
n_i	Lifespan of inverter
P	Present value
P_{ap}	Annual peak load
P_{bb}	Present value of buyback rate
$P_{cap,InV}$	Present value of capital cost
$P_{cred,fed}$	Present value of federal investment incentives
$P_{cred,state}$	Present value of state/local investment incentives
$P_{elecsav}$	Present value of energy savings
P_{geni}	Maximum power generated
P_{loadi}	Power demand
P_{min}	Minimum loading condition
P_{neti}	Net power load/demand
P_i	Present value of inverter replacement
$P_{O\&M}$	Present cost of operation and maintenance
$P_{PV,A}$	Annual PV output
$P_{PVex,A}$	Annual excess PV generation
$P_{PVus,A}$	Annual useful PV generation
$P_{PVsf,A}$	Annual energy shortfall from PV
P_s	Present value of cost of the system
$PV_{P_{PV,lt}}$	Present value of PV output over the lifespan
r_d	Annual performance degradation rate
$R_{inverters}$	Integer number of inverter replacement
W_{ac}	Watt of alternating current
W_{dc}	Watt of direct current
η	Panel efficiency
η_d	DC to AC derate factor

LIST OF ABBREVIATIONS

AC	Alternating Current
BOS	Balance od systems
CO_2	Carbon dioxide
CPI	Customer Price Index
CPV	Concentrating photovoltaic
DC	Direct Current
CF	Capacity factor
GHG	Greenhouse gas
IMBY	In MY Backyard
LCOE	Levelized cost of electricity
NOx	Nitrogen oxide
NREL	National Renewable Energy Laboratory
NPV	Net present value
OPA	Optimal area covered by PV
PVOBM	Optimal site based PV Performance Model
SAM	System Advisor Model
SO_2	Sulfur dioxide
TMY	Typical Metrological Year
TRNSYS	Transient System Simulation

LIST OF UNITS

Name	Unit
Temperature	Degree celcius (^{o}C)
Power	Watts (W)

CHAPTER 1

INTRODUCTION

1.1 Overview

Energy is essential for the current growing global economies. It is one of the main world's key challenges such as the migration of climate changes, the campaign for sustainable development and environmental protection issues [1]. In the last decades, world primary energy consumption has increased rapidly; the trend is projected to continue due to growth in both population and energy demand from developing countries [2]. Figure 1.1 is taken from Shell Sustainability Analysis report, displays the total energy demand pattern from 1980, on with projections of energy demand up to 2050 [3]. The same report projected that the energy demand in Asia (with rapidly expanding cities) could be doubled by the middle of the century from its level in 2000. According to International Energy Agency (IEA) report, the global energy demand is set to increase by 37% by 2040 in our central scenario, but the growth path for a growing world economy and population is less demanding than its usual [4].

The major consumer of energy in Peninsular Malaysia is the domestic sector (82.0%) [5]. Most of the energy is produced from natural gas (57%), and coal (34%) [5]. The energy production from fossil fuels has a significant effect on the environment due to greenhouse gas (GHG) emissions, air and water pollution due to the energy combustion and excessive land used for mining activities. Emissions released during the process of burning also generate residual products that cause severe health hazards. For instance, fly residue in the process of combustion comprises heavy metals, such as arsenic or mercury, and is extremely radioactive in nature [6]. Natural gas contributes to the dangerous releases and worldwide 24. 6% of greenhouse gas emissions (GHG) came from electrical energy and heat production whereby natural gas is the main source [7].

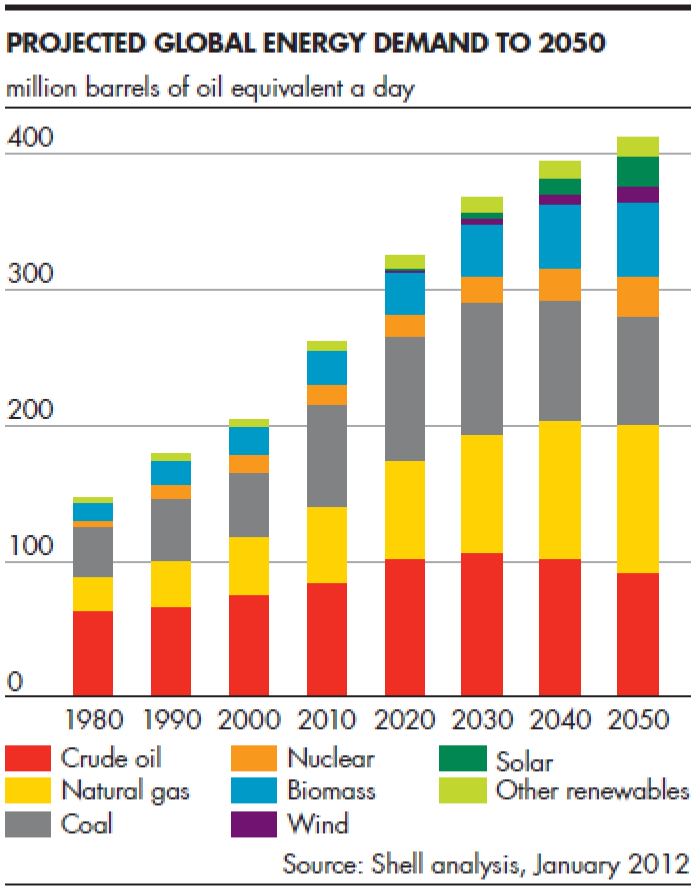

Figure 1.1: Projected global energy demand to 2050 based on Shell Analysis [3]

The status of energy dependency remains the current debating topic. The depletion of fossil fuel sources is currently a general subject of discussion for the research and development of sustainable techniques. For example, fossil fuel reserves the condition is twofold. In contrast, Malaysia is a net gas importer, but at the same time, it seems to have an insufficient indigenous resource of natural gas for future energy demand [5]. Based on Energy Independence and Security Act of 1981, 2000, and 2011, it is required to decrease the use of fossil fuel produced energy, invest into options of sustainability and thus, increase the share of renewable energy technologies [8,9]. In the year 2009, as a big step towards sustainable energy, the National Green Technology Policy proposed rules on the limit of carbon emission for both future and existing power plants, targeted to reduce the carbon emission intensity up to 40% by the year 2020 compared to 2005 levels [10]. This rule could result in the shutdown of several units of coal-fired power plants and improve investments in renewable energy systems and smart grid [11].

Compared to fossil fuels, renewable energy alternatives have zero potential or close to zero of GHG and other air pollution constituents [12]. In 2014, the worldwide contribution from renewable sources for electricity production was 30%, and in Malaysia renewable sources contributed less than 1% of the overall generated electricity [10, 13]. The contribution of each renewable source with projection to 2050 is presented in Table 1.1 and the annual electricity generation from renewable energy sources is presented in Figure 1.2 [10, 13].

As reported by the NREPAP (Table 1.1), Malaysian government targeted to achieve a 29 TWh per annum of electricity generated from RE sources with an installed capacity of 11.5 GW by 2050. This capacity may contribute about 15% of the total energy generated in the energy mix by 2050. As seen in the table, biomass is expected to contribute significantly to the total energy mix from 2015 until 2045 with about 27.5% of total generation from RE resources [10, 13].

Table 1.1: Projection of Renewable Energy by Source from 2015-2050 [10, 13]

Year	Annual Biomass (GWh)	Annual Biogas (GWh)	Annual Mini-Hydro (GWh)	Annual Solar PV (GWh)	Annual Solid Waste (GWh)	Annual RE Electricity (GWh)	*Cum RE (MW)
2015	2,024	613	1,450	61	1,223	5,374	975
2020	4,906	1,472	2,450	194	2,208	11,229	2,065
2025	7,297	2,146	2,450	456	2,330	14,680	2,809
2030	8,217	2,514	2,450	1,019	2,392	16,592	3,484
2035	8,217	2,514	2,450	2,128	2,453	17,762	4,317
2040	8,217	2,514	2,450	4,170	2,514	19,865	5,729
2045	8,217	2,514	2,450	7,765	2,575	23,522	8,034
2050	8,217	2,514	2,450	13,540	2,637	29,358	11,544

Meanwhile, electricity generation by solar is expected to play a significant role in the future (2050-upward). Based on the target, Solar PV has the largest capacity and high potential to meet the future growing electricity demand of the country. The impact of electricity generation from PV is expected to increase significantly due to the advance in technology, which comes with a high-efficiency solar panel [10, 13].

Figure 1.2 presents the yearly targets of energy generation from RE resources for the duration between 2015 and 2050. As depicted in the figure, until 2030 biomass is anticipated to be the highest contributor of energy on a yearly basis, followed by biogas and mini-hydro, with 50%, 15%, and 15%, respectively. However, Solar PV is expected to have the least contribution, with 2% of the total RE share. Based on 2050 projection, solar PV is seen to have the largest percentage of energy contribution followed by biomass, with 46% and 28% of RE share in the energy mix. While mini-hydro has the least contribution (8%).

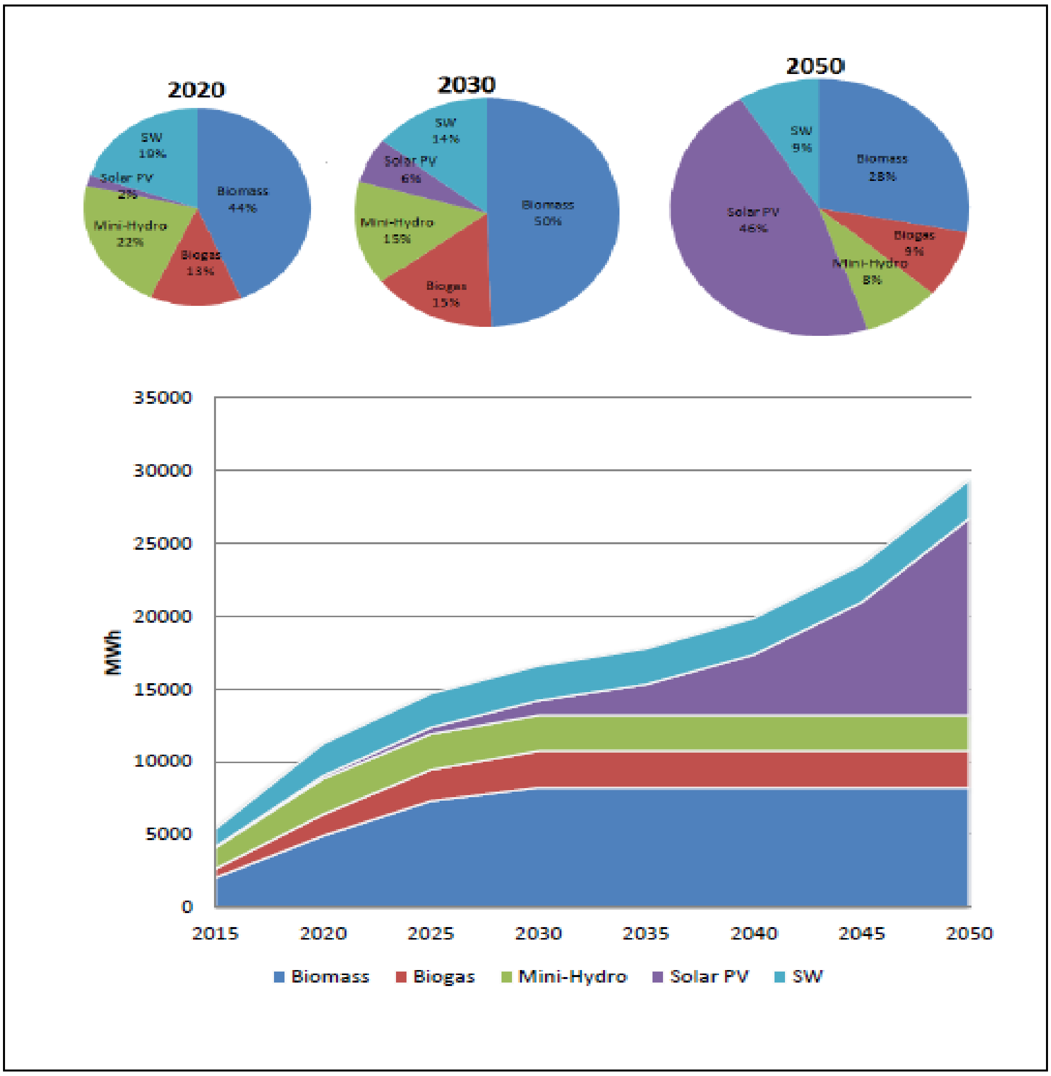

Figure 1.2: Projected Yearly Energy generation from Renewable energy sources, in Malaysia from 2015-2050 [10, 13]

This study was motivated by the growing electricity demand [14, 15], rising population in Peninsular Malaysia compared to East Malaysia [16-18], good solar radiation potential for PV installation [18-21] and the supporting policies for renewable energy application [9, 15, 22-25]. Also, PV technology is a technology for renewable energy production which provides enormous advantages. These advantages such as cleanest among other renewable sources since it does not generate noise and carbon dioxide (CO_2) or other global warming potential pollutants during operation [14]. Despite the advantages, PV energy possesses some disadvantages such as large land use requirements due to the current module efficiency and high manufacturing cost. Nevertheless, it shows a promising future. Solar PV is identified in various applications which include grid-connected, hybrid, and off-grid systems. The prices of the technology have been continuously reducing in the last few years and are predicted to drop even lesser [15]. However, PV systems provide better coincidence between generation and energy demand profiles for electricity compared to wind sources.

1.2 Problem statement

This study focuses on the evaluation of the technical limits of PV as a source of electricity generation in Peninsular Malaysia that can assist to reduce growing demand for electricity relative to the location, timing, and level of electricity demand. In order to evaluate the technical limits of large-scale PV systems which involve site suitability analysis for PV deployment and accurate prediction of PV output for matching generation and electricity demand.

In the near future, it is expected to have a strong increase in installed capacities of a large number of large-scale grid-connected PV power plants in Peninsular Malaysia for energy security and sustainability. However, land available for future installation of large-scale PV systems with long-term performance needs to be identified without compromising the conservation of all the precious national assets and heritages, particularly ecologically valuable land.

Recently, site selection for PV deployment has been achieved using Multi-Criteria Decision Methods (MCDM) combined with Geographic Information Systems (GIS) [26]. Analytical hierarchy Process (AHP), ELECTRE, and PROMETHEE integrated with GIS are the most popular MCDM for site selection [27-29]. Each of these techniques is identified with some issues, AHP suffers from inconsistency between judgment and criteria ranking due to interdependency between alternatives and criteria [30]. In ELECTEE technique, it is difficult to explain the process and result in layman's terms, also difficult to identify the weaknesses and strengths of the alternatives [30]. There is no clear methodology for assigning weights in PROMETHEE [30]. Generally, site selection using these popular outranking techniques of MCDM are limited by the need of pairwise comparison between alternatives, which is impractical as the number of alternatives is large [31] and depend on decision maker's preferences. In addition, these approaches provide the output in the form of suitability index map for visualization, awareness and decision support. Thus, it is not enough to consider suitability map as final for decision making, but in fact, suitable areas need to be fully disintegrated into parcels of land in order to understand the spatial variability between regions, such as optimal sites, installation capacity, energy generation potential, and environmental and economic benefits.

In order to enhance the performance of the existing GIS-based MCDM, a new method for optimal site selection must be proposed. The possible improvement involves simplifying the decision rule for comparing alternatives. In this study, a new method called Optimal site Definition Method (ODM) is proposed to eliminate the complexity of pairwise comparison between alternatives and dependancy on decision maker's preferences in MCDM. Consequently, by applying ODM, the limitations of GIS-based MCDM mentioned above can be eliminated. The proposed model should be able to select optimal sites in the form of parcels of land, without compromising the growing number of alternatives as well as the ecologically valuable area. In addition, this improves the performance of MCDM in the territorial studies and decision making due to its simplicity.

Globally, several studies concerning the benefits of large-scale PV penetration and other renewable resources into grid systems were conducted using different PV performance models [32] which performed well. However, most of these studies used physical models implemented in different software tools such as HOMER, TRANSYS, SAM, EnergyPLAN, etc., to evaluate the dynamic performance of PV systems [33-40]. Several models are directly applied to forecast the output of grid-connected PV plants either in real time [41] or in short-term [42, 43] or long-term conditions [44-46]. using different techniques to understand and enhance the system performance in various regions in the world. These physical models require specification of many variables, some of which were not available at most of the stations and expensive where they were available.

Although previous studies have attempted to evaluate large-scale PV integration into the existing grid systems, the most critical limitation in these studies, which are mainly based on physical models and technical parameters (voltage and current) through simulations, is the lack of connection to spatial planning activities. Concisely, energy prediction tools and models are mostly detached from the real world (from a geographic perspective) as they generally account only for topological relations within the system, neglecting the actual topography and spatial relationships. In addition, none of these studies have incorporated the topographical, topological features and geographic information systems (GIS) to assess the technical limits of large-scale PV implementation. Thus, integrating the geographic nature of renewable energy resources (PV), accounting not only for energy-related variables but also for spatial ones, is a perennial challenge.

However, in order to improve the performance of the existing tools and models for evaluating the technical limits, an alternative evaluation method needs to be proposed. In this research, a generation-demand matching model (GDMM) is proposed that effectively integrates topographical, topological features and GIS with energy prediction models to evaluate the practical limits and economic benefits of large-scale grid-connected PV power plants in Peninsular Malaysia.

1.3 Research Aim and Objectives

The aim of this research is to model the technical limits of large-scale PV power plants in Peninsular Malaysia by improving the performance of the existing tools and models for evaluating the limits through incorporating the spatial factors and GIS. It involves the development and implementation of an optimal site selection method using GIS, and generation and demand evaluation method using spatial factors. The research objectives are

1. to develop an ODM with GIS for selecting the optimal sites for large-scale PV power plants deployment.
2. to calculate the spatial distribution of technical potentials (GW), electricity generation potentials (GWh) and carbon emission reduction among the states of Peninsula based on the results of optimal sites.

3. to evaluate the impacts of large-scale PV generation on utility grid, economy, and emissions reductions using the proposed GDMM.

1.4 Scope and Limitation of the Research

The scope of this research covers large-scale grid-connected PV power plants installed in Peninsular Malaysia. Optimal site based Defination Model (PVOBM) have been developed as a simulation tool used to generate the time-series output profile of large-scale PV power plants. The optimal areas for large-scale PV power plant deployment are identified based on the proposed ODM. The effectiveness of the proposed ODM is assessed based on a hillshade and the recent land-use maps as discussed in Chapter 3. PVOBM is based on optimal area, solar radiation of the area, and efficiency of the commercially available PV modules. The effectiveness of the proposed PVOBM was evaluated using PVWatts simulation software developed by the National Renewable Energy Laboratory (NREL) as presented in Chapter 4. PV output profile based on PVOBM has been integrated with electricity demand profile using the proposed GDMM to evaluate the impacts of large-scale PV generation on utility grid as presented in Chapter 5. Furthermore, levelized cost of electricity and the impact of emissions offset by large-scale PV generation is evaluated as discussed in Chapter 6.

In order to utilize the most recent available data, solar radiation data for the year 2014 used for the hourly PV output simulations was selected based on the availability of electric demand data. To provide an accurate prediction of the future, long-term average data were used as a predictor of the performance in the long-term for economic and environmental analysis. The long-term average solar radiation data used is the recorded measurements over twenty-four years The sets of data used are discussed in Chapter 4.

Peninsular Malaysia was chosen because it contains all the parameters and available data considered in the proposed models. Moreover, its prime climate features are ideal for the optimal performance of large-scale PV power plants. It has the largest land area of about 131,598 km^2 About one-third of the surface area of Peninsular Malaysia is occupied by steep highlands (hills and mountains) and runs progressively in almost parallel to the country's axis [47]. Approximately 76% of the total population of Malaysian lives in Peninsular. GDP is the key variable driving the demand for electricity. In the long term, the Peninsular GDP is projected to remain strong at 5.9% per annum (2016-2020) and 6.2% per annum (2021-2030) [48]. The application of the models in this area allowed us to witness the impact of each selection criterion and large-scale PV penetration on the final result.

1.5 Thesis Organization

Chapter 2 covers literature review about the PV systems, electric utilities, PV performance prediction models, progress in sustainable power generation in Malaysia, solar energy and GIS and multicriteria decision for optimal site selection and the impact of large-scale grid-connected PV energy production on utilities. Chapter 3 discusses the development of optimal sites using the proposed model, prediction of technical potentials, and associated carbon emission reduction. Chapter 4 covers the simulation tools, data sets for simulations, and simulations results and discussions. Chapter 5 covers the impacts of large-scale PV penetration on the utility grid network and the contribution limits. Chapter 6 discusses the economic assessment with respect to the cost of energy generated from large-scale PV power plants and the estimated reductions in emissions from PV generation. Chapter 7 provides the summary of the findings, research contributions and limitations and some recommendation for future research.

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