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Spatial matching of large-scale grid-connected photovoltaic power generation with utility demand in Peninsular Malaysia

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HIGHLIGHTS

- A GDMM is proposed for matching generation and demand.
- Practical limits of large-scale PV with grid interaction.
- Quadruple energy point (QEP) is identified with PV penetration.
- Levelized cost of electricity from the PV compared to conventional power plants.

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ABSTRACT

Deployment of large-scale grid-connected photovoltaics (PV) 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 under-supply utility demand, thus requiring extra units of generators, while at higher penetration levels it may oversupply demands, thus wasting generator capacity. Thus, determining the optimum installed capacity, technical limits, and economic benefits of large-scale PV systems are the main issues for both power utilities and decision makers. This study describes the development and validation of an alternative method (called 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 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 performance located at optimal sites. Optimal sites along with physical constraints were mapped using 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. 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.

1. Introduction

The continuing decreasing cost of photovoltaics (PV) technology and increasing government subsidies has led to rapid growth in small-scale PV deployment. Both consumers and utilities accept solar PV as an alternative energy resource due to the lower costs and emissions during operation, as well as its ability to generate power during peak utility demand. Because governments are offering subsidies for the installation of PV plants and incentives for PV-generated electricity, it is becoming essential to evaluate the technical limits and benefits of producing electricity from PV systems on a large scale.

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Nomenclature

Symbols

$BtoC$	benefit to cost ratio
CS_i	cost savings for replacing a unit of energy production (RM)
C_s	installed cost of the system ($/W)
d	discount rate (%)
Em_i	total emission for a unit of energy production without PV (ton)
Em_{iPV}	total emission for a unit of energy production with PV (ton)
Em_p^n	emission rate for a unit of energy production with fuel type n (kg)
EP_i	energy generation without PV in year i (MW h)
Er_i^n	emission reduction for a unit of energy production with fuel type n (ton)
FF	flexibility factor (%)
G	irradiance at STC (1 kW/m^2)
HSR	hourly solar radiation on PV arrays (kW/m^2)
IC	installed capacity (kW$_{dc}$)
$LCOE$	levelized cost of electricity ($/kW h)
n	lifespan (years)
NPV	net present value ($)
NPV_C	net present value of total system costs ($)
NPV_B	net present value of total system benefits ($)
P_{ap}	annual peak load (MW)
PE_i^n	percentage of energy production in year i with fuel type n (%)
PV_{bb}	present value of buyback rate ($)
PV_{Cap}	present value of capital investment ($)
PV_{elsav}	present value of energy savings ($)
PV_i	present value of aggregate inverter replacements ($)
P_{geni}	maximum power generated (MW)
P_{loadi}	hourly load demand (MW)
$P_{load,A}$	annual energy demand (MW h)
P_{min}	minimum loading condition (%)
P_{neti}	hourly net load (MW)
P_{PVexi}	hourly excess PV generation (MW)
$P_{PV,A}$	annual PV generation (MW h)
$P_{PVex,A}$	annual excess PV generation (MW h)
$P_{PV,hi}$	hourly PV generation (MW)
$P_{PVus,A}$	annual useful PV generation (MW h)
$P_{PVsf,A}$	annual energy shortfall from PV (MW h)
P_{PVsfi}	hourly energy shortfall (MW)
P_s	present value of cost of the system ($)
$PV_{P_{PV,A1}}$	annual PV generation in year 1 (MW h)
$PV_{P_{PV,sl}}$	present value of PV output over the lifespan ($)
r_d	annual performance degradation rate (%)
UV_p^n	cost of reducing the emission with fuel type n (RM/kW h)

Indices

i	time step

Greek

η	efficiency of the panel (%)
η_d	DC to AC derate factor

Abbreviations and acronyms

AC	alternating current
BOS	balance of systems
CO_2	carbon dioxide
DC	direct current
GHG	greenhouse gas
LDC	load duration curve
NO_x	nitrogen oxide
NREL	National Renewable Energy Laboratory
PV	photovoltaic
PVOBM	optimal site based PV Performance Model
SAM	system advisor model
SO_2	sulfur dioxide
TMY	typical metrological year
TRNSYS	transient system simulation
NSRDB	National Solar Radiation Database

PV cells are made of semiconductor devices and convert incident irradiance into electricity. PV technology provides power from a renewable source and has numerous benefits [1]. As reported by [2], PV provides a better match between power generation and peak demand than wind, and PV technology is easy to install as distributed systems. The technology is familiar, so its recognition and acceptance by the public are encouraging. In spite of these benefits, the high cost of PV units has hindered considerable penetration in the marketplace, although PV unit cost has been decreasing over the last decade [3,4].

As of 2015, the cumulative installed PV capacity in Malaysia stood at 168 MW$_{dc}$ (1992–2014) [5], which is far below 0.1% of the total energy mix in Malaysia. In Peninsular Malaysia, the grid-connected installed PV capacity as of 2014 was 12.8 MW, also below 0.1% of the total energy mix. At this current low penetration level, PV production has little noticeable impact on the utility grid, but as the installed capacity increases, issues of the match between PV output and utility demand, short-range transients, and excess PV output become more critical [2].

The effects of large-scale grid-connected PV energy production on the utility grid system have received less attention than the impacts of wind-generated energy. This may be due to the proportion of energy generated by each of the two sources [2]. Several studies have analyzed the potential results of the large-scale integration of PV energy into several grid systems [6] or a combination of renewables [7–9] and the benefits [10–12].

Lund [13] assessed the large-scale integration of renewable energy sources (wind, PV, and wave) into the Danish grid system using EnergyPLAN software, focusing on the issues of incorporating power generated from intermittent renewable energy resource and electricity generation. The author found an optimal mix of PV, wind, and wave for application to the Danish grid system; furthermore, the result shows that integrating different renewable sources could minimize excess generation.

Hudson and Heilscher [14] identified many issues and challenges to power utilities when integrating large-scale PV systems into the utility grid. They clearly provide the codes and standards required for the integration of large-scale PV systems into the existing grid system. The results indicated that short-term fluctuations of the PV system are overcome with broad PV implementation. The authors finally highlighted three main: the need to evaluate the maximum level of distributed generation, increasing penetration of renewable sources, and balancing of energy sources.

In the state of Texas, a study conducted at National Renewable Energy Laboratory (NREL) attempted to assess the practical limit for PV generation as a fraction of total production [15]. Software for hybrid optimization of multiple energy resources (HOMER), produced originally by NREL, was used to simulate the power out-