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Optimum Capacity of Large-scale Grid-connected Photovoltaic Systems in Peninsular Malaysia

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ABSTRACT

Electricity generation using solar photovoltaic system has gained more acceptance than other renewableenergy sources due to its clean energy generation. It is now a common practice by the individuals, utilities, and government to generate electricity from the PV and integrate with the grid system. With an increasing PV penetration capacity, it is expected to have ageneration in excess of the demand, thus, warranting curtailment of generator units. Therefore, identifying the technical limit of PV without excess power is a concern for both policymakers and power companies. This study used Renewable Energy Optimization Matrix (REOM) to evaluate the optimal capacity of large-scale grid-connected PV implementation as well as solar PV share in the current Renewable Energy Plan with future demand in Peninsular Malaysia. The results show that a 100% utilization with 31.92% contribution to the total demand could be achieved with acapacity of 1.92 times the peak demand. The solar PV share in 2020 will also be 100% utilized and contribute 0.0018% of the overall demand.

Keywords: Large-scale PV system, Peak demand, Renewable energy plan

1. INTRODUCTION

Decrease in over-dependent on fossil fuel sources for electricity generation and integration of renewable energy resources into the existing utility grid system have been the current fashion globally. Malaysia is not exempted to this practice, and large-scale photovoltaics (PV) applications have increased significantly over the last few years in Malaysia. As of 2014, the cumulative installed PV capacity in Malaysia raised to 168 MW, the installed grid-connected PV systems grew from 48.2 MW in 2013 to 89.7 MW and penetration level of 0.2% [1]. This significant growth in PV installation is encouraged towards achieving the Malaysian national renewable energy (RE) plan of 2080 MW by 2020 [2].

The three main reasons for rapid growth in PV application in Malaysia are; firstly, a significant decrease in module prices over the last decade. According to the National Survey Report of PV Power Application in Malaysia (2014), module prices declined to about 80% of its price as of 2005, reduced from RM 21.39/W to RM 3/W in 2014 [3]. Secondly, technology development is also a major factor for growth due to the advance manufacturing process of the modules, increase efficiency, and lower levelized cost of electricity

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from large-scale PV systems. Lastly, government policies and utility incentives attached to the energy generated from PV systems.

On April 2010, Malaysian government passed a Malaysian National Renewable Energy Policy and Action plan (REP) to enhance utilization of RE resources and adopted as part of the national energy supply for security, sustainability, and socioeconomic development [2]. As reported by the Sustainable Energy Development Authority (SEDA), the Malaysian revised REP demanding 2% by 2015, 3% by 2020, and 3% by 2030 of Malaysia's energy sales to be supplied by renewable alternatives [4]. The Malaysian REP was established as part of the Malaysian RE Act 2011, and SEDA was established and charge with responsibility for realizing these goals. Ministry of Energy, Green Technology and Water, Malaysia (KeTTHA) provides the share expected from each indigenous RE (Biogas, Biomass, Solid waste, Small hydro, and Solar PV) to be contributed towards meeting national RE goals [5]. A 6% share of solar energy of RE goal (2020) equivalent to 0.0055% of Peninsular Malaysia annual electricity demand [5].

Under the current policy which needs solar electricity contribution in the national energy mix, and increasing the level of the installed PV capacity into the utility grid system, identifying the optimal penetration level in the energy mix is highly significant to both utility and policy makers to avoid excess generation. As the PV installed capacity continue to increase, it is expected to have a generation from the PV system in excess of the demand, especially under low demand and higher solar radiation in the absence of no energy storage facility or demand management.

Several studies have tried to evaluate the contribution limit of large-scale PV installation and few numbers have evaluated the optimum installed capacity of PV to be integrated into the traditional grid system [6-7]. Myer et. al [8] assessed the large-scale PV deployment in Wisconsin with respect to its interaction with the utility grid system, the economics of different installed capacity, and emission reduction. The study utilized the hourly simulated PV generation and hourly electricity demand. The results show that both economic and environmental benefits approach a limit with increasing levels of the installed PV system.

In Illinois, Jo et al [9] studied optimal penetration capacity of utility-scale PV system, technical and benefits into the power network using the Renewable Energy Optimization Matrix (REOM) based on hourly demand and simulated PV out. The share of PV under the Renewable energy Portfolio Standard (RPS) for Illinois was also addressed. The research reveals that the effect of high penetration of RE project is unrestricted to the benefits realized throughout the lifetime operation but rather the developmental stages of the development.

Several works have tried to evaluate the contribution of large-scale PV plant into the conventional grid system, yet these studies have not provided a methodology to apply to evaluate optimal penetration capacity of large-scale PV system into the grid system with no excess generation in the future. In addition, no approach to evaluate short and long-term national renewable energy plant.

The objective of this research is to evaluate the optimum installed capacity of large-scale PV application in Peninsular Malaysia by 2020 and effective contribution of 6% PV share by 2020 as specified in the current national renewable energy goals. To also evaluate the reliability of REOM in the tropical power system of Peninsular Malaysia.

2. COLLECTION OF DATA

2.1. Peninsular Malaysia Electric Utility Demand

The majority of power stations are located on the West coast, which is near to the demand areas. These power generation plants are connected to the demand centers via 500kV, 275kV and grid systems. To the northern Peninsular, the transmission line is also interconnected with generation stations in neighboring countries via 300 kV HVDC link to Southern Thailand of 300 MW capacity, 132 kVAC link to Sadao, Southern Thailand of 80 MW capacity. Also, 275/230KV HVAC links Singapore power grid (450 MW) to the southern Peninsular. The total installed capacity of power generation system was 21060 MW in 2014 [10]. Hourly demand data from the all the load centers are gathered by Energy Commission Malaysia. The annual peak load was 16901 MW. This study used hourly electrical demand data for the year 2014 which is projected to provide the demand data for 2020.

Figure 1a presents the histogram of the total electricity demand in Peninsular Malaysia for 2020 separated into 10% peak load intervals (i.e. 90% - 100%, 80% - 90%, etc.). The figure demonstrates the percentage of the year that the system worked within the interval of peak load. For instance, the system operates for 0.1285% (1126 hrs) of the year to provide end-use demand between 90% - 100% of the peak load. The fraction of demand in the range between 80% -90% of the peak demand is seen to be the highest with 0.304% (2666 hrs) of the year.

It is essential to notice that the greater proportions of peak demand specifically above 0.7 happened during the summer months, particularly June (Energy Commission Malaysia). These greater proportions of peak demand were maybe as a result of the weather condition and extra events during the school holidays which indicates greater electricity consumption.

As the capacity of the installed PV system increases, the power output from the PV plants begins to offset other sources in the generation mix [6, 8]. Power generated by the PV system may compensate the

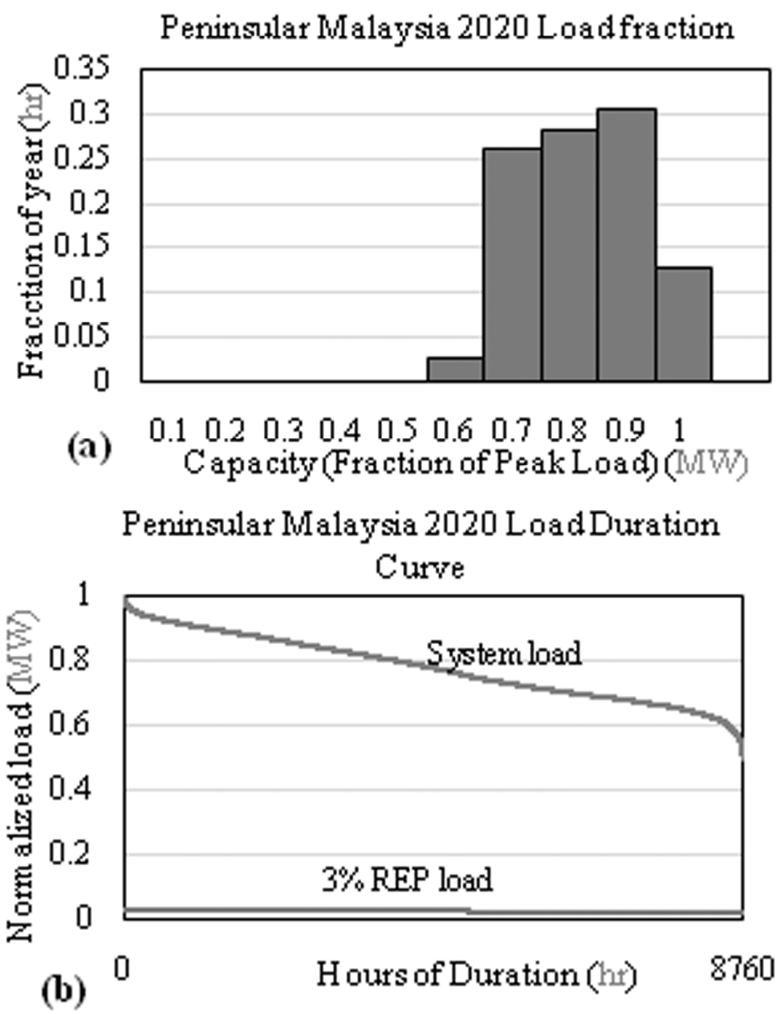


Figure 2.1: Annual demand: (a) histogram for the utility load fraction for 2020 in Peninsular Malaysia, (b) the normalized load duration curve for minimum loading condition

midday demand with minimal economic consequences. Meanwhile, it is important to note that PV systems cannot supply power for the whole day, so baseload power from conventional power sources is necessary. The conventional energy generators cannot reduce output below baseload power without economic penalty [6, 8]. The capacity of the baseload power comes from the product of annual peak load and the fraction of minimum loading. It is important to determine the system minimum loading in Peninsular Malaysia to understand the capacity of net load that could be contributed from renewable alternatives. The minimum loading is originated from Load Duration Curve (LDC) which is a collection of hourly load demand over the year at a fraction of peak demand sorted in descending order (figure 1b). The minimum loading was identified as 49.7% of the peak load as seen in the LCD (figure 1b).

2.2. Malaysia National Renewable Energy Plans (Rep)

The national REP with respect to the Peninsular Malaysia wants that 3% of the overall annual electricity consumption in Peninsular to be provided by renewable sources [4] and 6% of the 3% REP is mandated to be supplied by the PV system. The projected data of electricity consumption in 2020 (Eq. 1) were used to assess the solar PV share needed by the Peninsular Malaysia REP in 2020[9].

2.3. Peninsular Malaysia Solar Radiation Data

The study considers solar radiation data for the year 2014 collected from the meteorological station (MARDI) situated near Universiti Putra Malaysia. A complete year solar radiation data were measured at an interval of 30 minutes, and converted to hourly averaged data and then transformed to the irradiance on the PV array surface tilt angles [11–15]. These data were used to simulate the power output of the PV. The choice of the data is based on the available load demand data.

3. METHOD USED

3.1. Application of Renewable Energy Optimization Matrix (Reom) in PV Systems

In simulations of increasing installed capacity of PV, the systems could generate surplus power than required by the demand in some period during the day. The excess electricity generated by the PV is a waste and therefore rejected. For instance, there may be a period of low electricity demand and high PV production during high solar radiation. To determine the optimum installed PV capacity that can avoid the excess power generation and identify the PV capacity level that meets the national RE plant in Peninsular Malaysia, this study adopted the REOM approach developed by Jo et al. [9] in Illinois. Hourly electricity demand and the hourly simulated PV output based on solar radiation data for a complete year were used during the analysis.

The overall energy demand needed in 2020 (E_{T2020}) was projected based on 2014 total hourly power demand (E_{T2014}) collected from Energy Commission Malaysia (Eq. 1 and 2). The annual growth rate $\propto$ equal to 3.5% was obtained from Peninsular Malaysia electrical load projection for 2020 and was applied in the analysis.

$$E_{T2020} = E_{T2014} \times \left(1 + \propto\right)^{6} \tag{1}$$

$$E_{T2014} = \sum_{i=1}^{365} \left(P_i\right) \tag{2}$$

Since conventional power sources provide the baseload power which cannot be displaced by renewable sources, then the power to be replaced by renewable sources (P_{ri}) is evaluated using the baseload power (P_b) as given by equation (3)

$$P_{ri} = P_i - P_b \tag{3}$$

The simulated PV power output (P_{PVi}) was compared with the replaceable power (P_{ri}) at different levels of PV penetration. When the PV power out P_{PVi} is less than or equal to the replaceable power P_{ri}, then PV output used ($P_{PVusedi}$) is the same as P_{PVi} (Eq. (4)), no excess power from PV (Eq. (5)). Similarly, when P_{PVi} is greater than P_{ri}, $P_{PVusedi}$ is the same as P_{ri} (Eq. (6)), and the rejected/excess output PV (P_{PVexi}) is the difference between P_{PVi} and P_{ri} (Eq. (7)).

When: $P_{PVi} \leq P_{ri}$

$$P_{PVi} = P_{PVusedi} \tag{4}$$

$$P_{PVexi} = 0 \tag{5}$$

When: $P_{PVi} > P_{Exi}$:

$$P_{PVusedi} = P_{ri} \tag{6}$$

$$P_{PVexi} = P_{PVi} - P_{ri} \tag{7}$$

The above equations were applied to the total hours of the year (8769 h) to compute the annual electricity generated from the PV, total usable energy generated by the PV and total excess PV generation (Eq. (8)–(10)).

$$E_{PV} = \sum_{i=1}^{8760} \left(P_{PVi} \right) \tag{8}$$

$$E_{PVused} = \sum_{i=1}^{8760} \left(P_{PVusedi} \right) \tag{9}$$

$$E_{PVex} = \sum_{i=1}^{365} \left(P_{PVexi} \right) \tag{10}$$

However, the PV utilization (Eq. (11)), Peninsular Malaysia demand that can be reduced by PV production (Eq. (12)), and the Peninsular Malaysia RE plan (REP) that could be reduced by PV production were computed (Eq. (13) and (14)).

$$PV\ utilization\ rate = \frac{E_{PVused}}{E_{PV}} \tag{11}$$

$$Load\ met\ from\ PV = \frac{E_{PVused}}{E_{T2020}} \tag{12}$$

$$E_{REP} = E_{T2020} \times 0.03 \tag{13}$$

$$REP\ Load\ met\ from\ PV = \frac{E_{PVused}}{E_{REP}} \tag{14}$$

In this study, two scenarios were investigated using the REOM approach. The two scenarios investigate optimum installed capacity and load reduction regarding the PV application relative to overall and REP demand. Scenario 1 quantifies the capacity of PV needed to install to meet 6% solar share from REP specifications. Scenario 2 identifies the PV installed capacity with 100% utilization (no excess generation).

3.2. Photovoltaic (PV) Performance Model

A simple model called Irradiance Based Model (IBM) was used to simulate the output of PV plants. Solar radiation and manufacturer's specifications were utilized to generate the PV output. A monocrystalline module of 16% efficiency was chosen for the simulations. The model can predict the hourly total electrical output of a large-scale PV plant using irradiance and direct area covered by PV arrays. The simple PV model equation is expressed as

$$P_{PVgeni} = A \times ASR \times \ \times {}_{d} \quad (15)$$

P_{PVgeni} is the instantaneous electrical power from a PV (Wh), A is the direct area covered by PV arrays (km^2), ASR is the hourly average solar radiation (kWh/m^2), is the efficiency of the panel (%), and ${}_{d}$ is the overall DC to AC derate factor (%).

The analysis conducted considered the orientation and fixed tilt angle of the PV arrays were due south and 15^{o} respectively[16], with the expectation that single owners at various locations who installed PV plants would maintain the same assumption to produce the maximum power per annum. The Direct current (DC) power output from the PV arrays was converted to Alternating Current (AC) power output which is reduced by a conversion factor. The derate factorconsidered in this study was 0.77 as proposed by NREL [17].

Table 3.1
Monthly AC generation per 10 MW installed PV capacity in Peninsular Malaysia

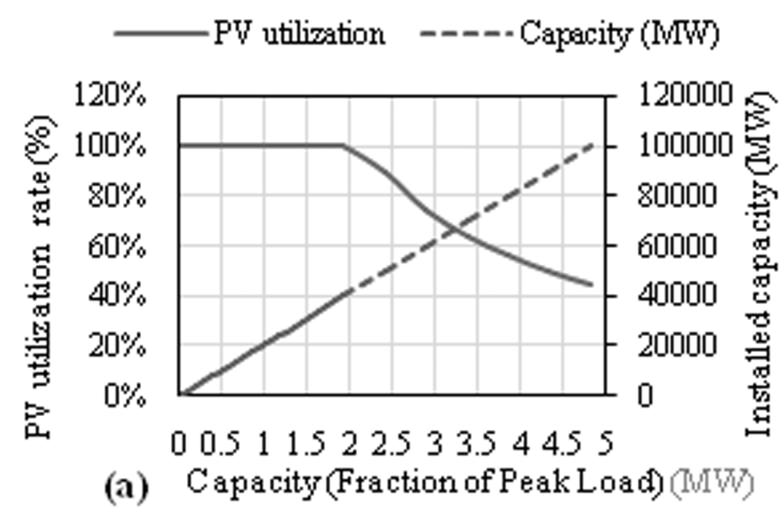
Month	1	2	3	4	5	6	7	8	9	10	11	12
Generation (GWh)	1.015	0.852	1.137	0.914	0.986	0.891	0.847	0.920	0.955	1.084	0.892	0.864

Table 3.1 presents the predicted monthly generation from a 10 MW PV plant. High PV production was recorded during the first and the last quarter months of the year due to the high solar radiation in that period.

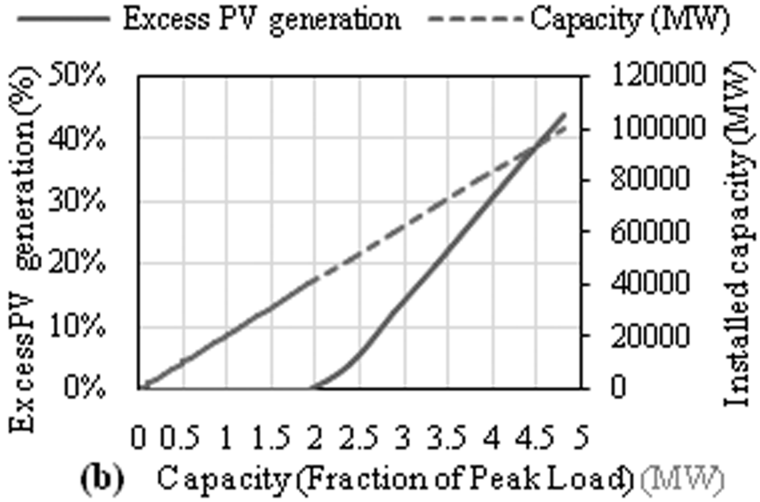
4. RESULT AND DISCUSSIONS

4.1. Optimum PV Capacity

As the PV penetration level increases, the percentage of PV utilization also increases up to the capacity where the effect of baseload power from conventional generators manifested. As seen in Figure 2a, a 100% PV utilization begins to drop at around 1.92 times the peak load (40,000 MW) which will contribute 31.92% of the total annual demand in Peninsular Malaysia by 2020. Meaning that as the installed PV capacity is beyond this optimal level, the greater the excess generation from the PV (figure 2a) and the less energy is utilized. Figure 2b shows the growth of excess PV electricity production as a function of installed capacity. In addition, the figure justifies that at lower penetration level, there is no surplus power, but at any capacity exceeding 1.92 of the peak demand, the excess generation grows significantly.



(a)



(b)

Figure 4.1: PV generation: (a) PV utilization against installed PV capacity and (b) excess PV generation against installed PV capacity

Table 1
PV capacity and production at two scenarios

Load profile		*6% PV share*	*100% utilization*
REP load (2020)	System capacity (MW)	230	3600
	Annual demand (MWh)	4234648.76	4234649
	Electricity generation (MWh)	254078.926	4055501
	System load met from PV (%)	0.0018	2.87
	REP load met from PV (%)	6	95.8

Table 1 shows the results of the two scenarios based on REOM and IBM. From scenario one, to realize the projected PV share of 6% of REP in Peninsular Malaysia, an aggregate installed PV capacity 230 MW is required to supply 254 GWh of electricity. This amount will reduce the overall system demand by 0.0018% in Peninsular Malaysia from the PV systems, thus equal to the 6% contribution from the PV as the REP requirement. The second scenario denotes the maximum capacity of PV need to be installed which will generate electricity without any surplus. This is the highest PV penetration level where PV utilization is 100%. To realize this capacity, a total of 3600 MW is required to be installed which will supply 4,056 GWh of energy and reduce 2.87% of the total energy demand as well as 95% of 6% of Peninsular Malaysia's REP by 2020.

5. CONCLUSION

This study has presented the REOM approach to identify the optimal penetration capacity of PV systems into the utility grid system and evaluate the 2020 solar PV share of REP in Peninsular Malaysia. The approach enables researchers to predict and make proper energy planning in the current and future time. The results show that the optimum installed PV capacity is 1.92 times the peak demand and will reduce the annual demand by 31.92% without waste. The power generated from the deployed PV plants at the capacity of the present PV share of 6% of the REP in Peninsular Malaysia would be 100% utilized without any surplus. The pattern of the results obtained in the tropical power systems is similar to that found in the study of Illinois power systems, this shows the robustness of the model. Determining the maximum installed capacity of large-scale PV plants plus technical limit are most pressing issues for both decision makers and power companies. We believe the approach used in this research to evaluate the PV penetration level in the future will assist decision makers in the development and planning for the future energy in their respective regions.

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