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Photovoltaic Deployment Experience and Technical Potential in Indonesia's Java-Madura-Bali Electricity Grid

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Abstract

The largest and most established electricity grid in Indonesia, the Java-Madura-Bali (JAMALI) interconnected system, accounts for around 60% of the country's total electricity demand. Given continuing high demand growth and the slow addition of major generators in recent years, energy users served by the JAMALI grid are experiencing inadequate and unreliable electricity supply. There is growing interest in the potential of renewable energy to help mitigate the risks of continued fossil fuel dependence, improve system reserve margins, and diversify energy sources to enhance supply security, as well as improve environmental outcomes. The Indonesian government's vision to increase the renewable energy contribution to Indonesia's energy mix to 23% by 2025, raises the question of what role utility-scale photovoltaic (PV) generation might play in meeting these challenges and opportunities. Indonesia has an excellent solar resource, while PV costs have fallen markedly over recent years. Still, the JAMALI's present generation mix is dominated by low cost and relatively abundant coal and gas.

This paper reviews the current status and future potential of utility PV in the JAMALI area. Given limited existing studies on solar irradiation and PV mapping for the Indonesian context, we first present a detailed spatial mapping of PV output potential for the JAMALI region including hourly temporal behavior – a key factor for assessing PV integration challenges and opportunities. This proposed spatial PV output mapping is provided at a 5 km² resolution, using weather data derived from the NASA MERRA-2 satellite database and the Global Solar Energy Estimator model. The mapping provides a preliminary indication of appropriate utility-scale PV locations in the JAMALI context. An open-source generation mix model, NEMO, is then used to assess the potential role of utility PV in least cost future generation portfolios for JAMALI. Results suggest that PV could play a useful role, depending on future technology, fuel and carbon prices, and demand growth. On this basis, current policies and regulations relevant to deployment of large scale PV are described and a number of key challenges for PV deployment and possible opportunities for reform are identified.



1. Introduction

The Indonesian government is facing great challenges yet also opportunities to improve the nation's future energy mix, contributing to international efforts to avoid dangerous global warming while also improving energy access and security. At the 21st United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP) in Paris in 2015, Indonesia announced an ambitious target to reduce greenhouse gas emissions by up to 29% compared to the business as usual level by 2030. One element of this is a target of 23% renewables in its overall energy mix by 2025. Among all commercially available renewable generation technologies, the role of solar photovoltaics (PV) seems certain to be crucial in supporting efforts towards these goals, in particular because of the rapid decrease in solar PV system prices in recent years.

Few studies, however, have been carried out to date assessing solar PV potential in Indonesia. The energy generation potential and cost-effectiveness of grid-connected PV systems at Indonesia's provincial level has been assessed by Veldhuis and Reinders (2013). However, the time interval in terms of PV potential is not clearly specified in the study. Solar radiation analysis has been conducted by Parangtopo et al. (1984), who analyzed global and diffuse solar irradiation (GHI and DNI) in Jakarta, while multi years solar radiation data for 10 locations in Indonesia and 2 neighboring locations in Singapore and Darwin, Australia, has also been analyzed (Morison and Sudjito, 1992). The study found that solar radiation across Indonesia shows a significant east-west gradient. Another study focused on the estimation of global solar radiation in the Indonesian climatic region (Halawa and Sugiyatno, 2001). The study presented monthly average daily global solar radiation correlations applicable to the Indonesian climatic region using a modified version of Sayigh's formula. Mapping of solar irradiation for each province in Indonesia, based on an artificial intelligence technique, has been conducted by Rumbayan et al. (2012). The study however, published only a single range of monthly values of solar irradiation for each province using a yearly average NASA database. Mapping of Indonesia's long term monthly average global horizontal irradiation and direct normal irradiation, and PV output potential funded by the World Bank's ESMAP program was recently published by Solargis (2017), based on their model.

While these reports provide long term averages that describe the solar resource at different locations in Indonesia, and can be used as a preliminary step towards prospecting for PV plant development opportunities, no analyses of temporal and spatial variability were reported in this studies. For power system planning, the variability of the output of PV systems over time, and the correlation of the output of PV in different locations are important in determining the potential aggregate PV generation ramp rates that must be managed by the power system.

Given the limited studies on utilizing PV resources mapping for assessing challenges and opportunities of large scale PV integration in Indonesia, this paper presents mapping of the temporal variability of PV generation output in the largest interconnected power grid in Indonesia; the Java, Madura and Bali electricity grid, or hereafter "JAMALI". On this basis, sites were then selected for a preliminary investigation into possible least cost future utility-scale PV investment in JAMALI using the National Electricity Market Optimizer (NEMO) tool (Elliston, et al, 2012)

This paper is organized as follows: the status of PV deployment in Indonesia and JAMALI is described in the next section. PV resource mapping in JAMALI is presented in Section 3. A



simulation of a least cost generation mix in JAMALI with high PV penetration is presented in Section 4, followed by discussions around policy recommendations, conclusions and future work in Sections 5 and 6.

2. Status of PV Deployment in Indonesia and in JAMALI

JAMALI covers two special regions and five provinces; that is, Jakarta, Yogyakarta, Banten, West Java, Central Java, East Java and Bali. It has about 19,500 kilometers of 150 kV and 500 kV transmission line. JAMALI relies heavily on coal (47% of total generation), gas (21%), and a small number of hydro and geothermal power stations to meet annual demand of more than 180 TWh, and 33.2 GW peak load in 2016. It represents around 60% of total national electricity generation (PLN, 2017).

Despite an excellent solar resource, averaging 4.8 kWh/m²/day across the country (PLN, 2017), significant deployment of grid-connected PV has not yet occurred in Indonesia. The International Renewable Energy Agency has estimated that there is some 39 GW of solar PV potential in the JAMALI area (IRENA, 2017).Still, by 2015, national installed capacity of utility-scale PV had reached only 9 MW with no installations in the JAMALI grid. During 2016, the capacity only slightly increased to 13 MW, with only 1 MW capacity in the JAMALI area (PLN, 2017). As part of the government's plan toward 100% electricity access for the Indonesian people, the limited budget allocated to support PV is mainly directed towards the promotion of off-grid PV for supporting electricity provision in rural areas, and in particular reducing diesel consumption on isolated mini-grids. The Indonesian government has encouraged Independent Power Producers (IPPs) to construct and operate such PV plants, and as a result, more than 71 MW of off-grid PV capacity was installed by 2016 (DG NREEC, 2016), compared to 13 MW on the grid.

Despite the limited budget to date, an overall national target of 6.4 GW of PV capacity by 2025 has been set by the government (IRENA, 2017). Initial support for IPPs involved a government regulated feed-in tariff up to US0.25/kWh with an additional incentive of 0.05c/kWh for PV systems with minimum 40% local content (that is, 40% of the overall value of the PV system should be produced locally). Under this framework, the maximum PV capacity allowance for each developer is limited to a maximum 20% of the regional capacity quota for the tender offer of 10–100 MW (MEMR, 2016). The first stage capacity quota and feed-in price for provinces in Java are 150 MW and US0.145/kWh, and 5 MW and US0.16/kWh for Bali provinces. Feed-in price for other regions, vary from US0.15 - 0.25/kWh (MEMR, 2016).

More recently, following a lawsuit brought by the local PV industry over foreign IPPs, the incentive was replaced with a different framework forcing PLN to buy PV energy from the IPPs. Under this framework, the feed-in tariff for PV generation ranges from 85% - 100% of the PLN regional electricity generation cost, while other rules stipulated in the previous framework remain active.

PLN opened a tender in the first half of 2017 for 168 MW of PV capacity (The Jakarta Post, 2017), in addition to 87 MW of recently planned capacity (PLN, 2017) in Sumatra. Nevertheless, this capacity is only a fraction of the 6.4 GW utility-scale PV goal for Indonesia over the next 10 years, and the long-term policy for achieving this is as yet unclear.



3. JAMALI PV resource mapping

Given the significant deployment of utility scale PV expected in the JAMALI region, it is important to better understand the underlying PV resource available across the region. For our study, one-year of gridded hourly PV power output data across the JAMALI region was obtained from the online renewable energy simulation tool Renewables Ninja (Pfenninger and Staffel, 2016). The data covers 2015, with a spatial resolution of 0.05° x 0.05° (5 km x 5 km). Renewables.ninja models hourly timestep PV output at a specific tilt angle based on NASA MERRA2 direct and diffuse irradiation, and ground temperature data, using the Global Solar Energy Estimator (GSEE) model (Pfenninger and Staffel, 2016). Figure 1 presents a map of PV capacity factor across JAMALI in 2015, which varies between 16.9% - 18.7%. A relatively high capacity factor can be seen in Bali (the island at the right side of Java) and in the southeastern part of East Java province.



Figure 1. Mapping of 1-year PV capacity factor across locations in JAMALI in 2015

Of course, effective and economically efficient PV integration will depend greatly on the patterns of PV generation across daily and seasonal cycles. A mapping of monthly PV capacity factor is presented in Appendix 1 while the range of monthly PV capacity factors for all JAMALI locations is presented in Figure 2. The three months with the highest monthly capacity factors are September, October, and August, of which the highest median capacity factor was 23.63% (September), while the lowest median capacity factor was April (11.87%). This significant seasonal variation poses some challenges for PV integration.



Figure 2. Range of monthly PV capacity factor for all JAMALI locations in 2015



3.1. Hourly output variability

Integration of high penetrations of variable renewable energy such as PV into power systems adds to underlying variability in demand, and increases the challenge of supply demand matching. Changes in PV power output require other generation units to ramp up to maintain the demand and generation balance, requiring sufficient spinning dispatchable generation to be available. This can be challenging at high penetrations, particularly where PV plant output is correlated and large changes in aggregate PV output occur. While managing variability and uncertainty presents challenges over a range of different timeframes, this study evaluates the hourly variability of PV power output. JAMALI dispatch is planned in half hourly basis. Of course, PV and demand variability over shorter time frames also poses operational challenges. However, higher frequency data of temporal PV power output for JAMALI is not available.

The method used in this paper for analysing variability is based on Mills and Wiser (2010). Change in average power output is calculated as follows:

$$\Delta P_1^{\overline{1hr}}(t) = P_1^{\overline{1hr}}(t) - P_1^{\overline{1hr}}(t-1)$$
(1)

where $\Delta P_1^{\overline{1hr}}(t)$ is the value of delta power output for 1 hour interval at a single site P_1 for hour t. The standard deviation of the variability (step changes between each hour interval) is defined as:

$$\sigma_{\Delta P_1}^{\overline{1hr}} = \sqrt{Var(\Delta P_1^{\overline{1hr}})}$$
(2)

The 99.7th percentile (three standard deviations, 3σ) value is used as an indicator of the range of variability.

Figure 3 shows the range of hourly variability across all locations in the JAMALI grid expressed as 3σ variability. These fall within a range of 230 - 254 kW/hr change per 1 MW PV plant capacity. Overall, there is roughly 10% difference between locations with the lowest and highest range of variability, roughly equivalent to the 10% difference in capacity factors seen across the JAMALI region.



Figure 3. Mapping of 2015 hourly ramp rate variability across JAMALI (in 3σ)

The range of values of 3σ variability across all locations in JAMALI are shown by month in Figure 4. High variability occurred in the same months having high capacity factor, i.e. September, October, and August. During these three months, the values of 3σ variability were 0.28 - 0.3 MW/hr per 1 MW plant capacity.



One key question for integration is the effect of PV plant diversity on aggregate output; that is how variability is impacted when PV generation is distributed across multiple, geographically dispersed locations. As more variability of PV output in intra hour resolution is expected, the aggregated variability of multiple disperse PV systems would be less so that intra hour variability will be reduced using 1-hour data. To assess this, one location from each province (the small provinces of Jakarta and Banten are merged) was selected, based on sites with the best capacity factor. Another 19 locations with more varied capacity factors and ramp rates were then added to these 6 provincial locations, in order to compare the cumulative distribution delta of PV output. Figure 5 presents the cumulative delta of PV output (in absolute values) for 6 and 25 aggregated locations.



Figure 4. Monthly maximum – minimum variability of hourly ramp rate across locations in JAMALI in 2015, expressed in 3σ



Figure 5. Top 10% cumulative distribution of delta P for 6 aggregated sites (left) and 25 aggregated sites (right)

The top 10% of the aggregated delta P ranges between 0.17 - 0.22 MW/hr per MW installed aggregated capacity, for both the 6 and 25 aggregated PV locations. In practice, this gives an idea of how much adjustment would be required from other generators in terms of their hourly output in order to maintain supply – demand balance in JAMALI. This would be equivalent to 650 - 850 MW/hr given a 3.84 GW capacity (equivalent to assuming 60% of the 6.4 GW



Indonesian 2025 PV target was deployed in the JAMALI grid, which supplies 60% of demand in Indonesia). Figure 6 presents a comparison of the cumulative distribution of the delta PV output for 1, 6 and 25 aggregated locations. The magnitude of delta P is slightly decreased from 0.24 to 0.22 MW/hr per MW installed capacity from a single site to 6 aggregated locations or more.



Figure 6. Comparison of the cumulative distribution of deltas P for 1, 6 and 25 aggregated locations with normalized absolute delta P

4. PV integration in JAMALI's long-term generation mix

This Section offers insights into the potential role of large scale PV in the future JAMALI system, through preliminary results of modelling of JAMALI's least-cost long-term generation expansion options. The simulation is conducted using NEMO, an open source evolutionary algorithm-based optimization tool, which was developed and used to study Australia's future electricity generation mix with 100% renewable energy (Elliston, et al, 2012). Solutions for generation mix are obtained by minimising cost of energy while complying with a set of constraints.

4.1. Model inputs

For this study, 2015 JAMALI hourly demand data was used (PLN, 2017) as a baseline, and 3.5% to 10% linear annual growth was added to create a projected 2030 demand profile. All generators in 2030 are costed as new build. For this purpose, baseline technology costs for 2015 are taken from an Indonesian government agency report (National Energy Council, 2016) and technology cost scenarios for 2030 are scaled from the baseline by using 2015 – 2030 cost escalation trends provided by NREL (NREL 2017). The international trends are considered to be relevant, since most the technologies are largely imported. Indonesia's coal and gas price projections for 2030 are obtained from IRENA (IRENA, 2017). A Loss of Load Probability (LOLP) of 0.274% (equivalent with 24 hours in a year, where demand cannot be meet by available generation) is used in all scenarios in accordance with the Indonesian reliability standard (PLN, 2017). In addition, the carbon price and discount rate are assumed to be US\$ 25/tonne of CO₂ equivalent and 5% in 2030, respectively as suggested in Elliston, et al (2012).



Coal, gas, hydro, biomass, geothermal and PV are modelled as generation mix candidates using NEMO. Build limits (GW) are set for hydro and geothermal at 8 and 10 GW, respectively (DG NREEC, 2016a). To model potential PV generation, the JAMALI area was divided into 6 polygons based on provincial classification, and each polygon assigned a PV plant candidate trace, of which the PVs build limit (GW) were capped according to each polygon's potential output. The provision of traces from each region to the NEMO investment optimisation model provides an equal opportunity for PV to be built in each region. The PV plant candidate in each polygon was chosen according to three factors: high capacity factor, low hourly temporal variability and low spatial variability. The selected locations are therefore mostly in the southern part of JAMALI where capacity factors are high (Figure 1). An additional benefit of these locations is that they are relatively far away from the central part of the islands, which have volcanoes and difficult terrain (highlands).

Other considerations for PV plant locations could include the similarity between each site's output (Elliston, et al., 2016). In this case, the coefficient of correlation between polygon 1 (western part of JAMALI) and polygons 2 - 6 are within 0.95 to 0.97, indicating that hourly output is highly correlated across JAMALI. The highest coefficient of correlation is found between polygons 3 and 4, which is 0.99, which would make a combination of PV plants at these two locations less complementary in terms of benefiting from generation diversity.

Several scenarios that consider changes in future technology costs, future gas price and future demand are simulated in order to reveal possible least cost generation mixes that meet the specified reliability level.

4.2. Reference Scenario and Results

The reference scenario (Table 1) 2030 mid-level technology costs, 346.5 TWh demand (vs 166.6 TWh demand in 2015), a US\$ 10.9/GJ gas price, US\$ 3.5/GJ coal price, and 0.274% LOLP standard

Reference scenario: LOLP 0.274%, cost scenario: 2030-mid,								
demand: 346.5 TWh, gas price US\$ 10.9/GJ								
Unused surplus energy (TWh)	0.0							
Time steps with unused surplus energy (hr)	15							
Min – max shortfalls (MWh)	0.0, 696							
Unserved energy (%)	0.002							
Unserved total hours	24							
Loss of Load (%)	0.27							
Total hour of Loss of Load (hr)	24							
System generation cost (US\$/MWh)	50.38							
Total emissions (MtCO ₂)	108.94							

 Table 1. System parameters of the reference scenario

The results of simulating the reference scenario are shown in Table 2. Flexible fossil fuelbased generators (coal fired, CCGT, and OCGT) account for 30.88% and 41.46% of the total capacity and energy generation 2030. Geothermal and hydro contribute 25.25% and 20% of the total energy generation, respectively. Meanwhile, PV's contribution is quite substantial with PV generation built in all regions except Yogyakarta. The total PV capacity and energy generation are 28.91 GW and 46.2 TWh, respectively, accounting for 37.16% and 13.34% of



the total capacity and energy generation in the JAMALI. Under the chosen technology, fuel and carbon costs, these results suggest that PV is already a cost effective generation option and would be part of an economically least cost, green fields, generation mix for JAMALI. Levelised Cost of Energy (LCOE) and capacity factors for each generator in the optimisation are shown in Figure 7.

Reference scenario:										
LOLP 0.274%, technology costs: 2030Mid, demand: 346.5 TWh, gas price: US\$ 10.9/GJ										
Technology		Java 1 (Banten + Jakarta)	Java 2 (West Java)	Java 3 (Central Java)	Java 4 (Yogya)	Java 5 (East Java)	Bali 6 (Bali)	Total	%	
Solar PV	Cap (GW)	4	9	2.91	0	11	2	28.91	37.16	
	Energy (TWh)	6.087	14.27	4.651	0	17.95	3.248	46.21	13.34	
Geothermal	Cap (GW)	10						10	12.86	
	Energy (TWh)	87.49						87.49	25.25	
Hydro	Cap (GW)	8						8	10.28	
	Energy (TWh)	69.1						69.1	19.95	
Coal	Cap (GW)	22.3						22.3	28.67	
	Energy (TWh)	137.5						137.5	39.69	
CCGT	Cap (GW)	5.51						5.51	7.08	
	Energy (TWh)	5.585						5.585	1.61	
OCGT	Cap (GW)	3.07						3.07	3.95	
0000	Energy (TWh)	0.5582						0.558	0.16	
Total capacity (GW)							77.79	100		
Total energy supplied (TWh)							346.4	100		

Table 2. Generation and capacity mix of the reference scenario in 2030



Figure 7. LCOE and capacity factor of the generators, given LOLP at 0.274%, cost scenario: 2030-mid, demand: 346.5 TWh, gas price: US\$ 10.9/GJ

4.3. Demand Growth and Technology Cost Scenarios

The impact of different possible future electricity demand, technology and gas prices were also investigated. Three technology costs scenarios, i.e. 2030 low, mid and high were used along with gas prices of US\$ 7/GJ, US\$ 10.9/GJ and US\$ 15/GJ, and 4 demand levels, 279.9



TWh, 346.5 TWh, 493.1 TWh and 696.3 TWh (3.5%, 5%, 7.5% and 10% annual growth from 2015). Historical inter-year average demand growth rate in JAMALI was measured around 5% over 10 years, with annual load growth was ranging around those selected demand levels.

PV capacity could vary between 2 GW to 24 GW for the first demand level and between 4 GW to 35 GW for other demand levels, depending on the gas price. PV capacity would be the lowest for all cases in the high technology cost scenario and highest for the low cost scenario. Meanwhile, other generators' aggregated capacity are relatively stable at 40 GW, 50 GW, 70 GW and 98 GW for demand level of 279.9 TWh, 346.5 TWh, 493.1 TWh and 696.3 TWh, respectively, given various cost scenarios and gas price. PV's contribution to the generation mix could range between 5% - 14.4% for 346.5 TWh energy demand profile (5% annual demand growth vs 2015). This accounts the highest share of PV generation mix among other demand – cost scenario levels, despite relatively low share among other technologies. Figure 8 (left) shows PV and other generator's aggregated capacity for all demand, all cost scenarios and all gas price US\$ 10.9/GJ.



Figure 8. (left) PV Capacity (GW) versus other generators' aggregated capacity for all demand, cost and gas prices scenarios; (right) Energy mix (%) for all demand and cost scenarios at a gas price US\$ 10.9/GJ



Figure 9. Changes in generation costs (US\$/MWh) and CO₂ emissions (MtCO₂) for all costs, demand and gas price scenarios

Figure 9 (left) shows changes in average generation costs and CO2 emissions for all costs and demand scenarios with the different gas prices. Average generation cost varies from 41.31 - 62 (US\$/MWh) for all costs scenarios. With a 279.9 TWh annual demand, the cost ranges between 41.31 - 48.25, while with 696.3 TWh annual demand, costs range from 58 - 62.02. CO₂ emissions could be as low as 132 MtCO₂ for 493 TWh demand in the high cost scenario



and a gas price of US\$ 7/GJ, due to the elimination of coal fired plants in the system, replaced by significant CCGT and a few GW of OCGT.

5. Discussions

The results of simulations conducted for this research suggest that a substantial capacity of PV; that is 25 - 35% of the total system GW capacity could be part of a least-cost 2030 generation mix for JAMALI under a modest carbon price, with only a relatively small variation in PV deployment given different gas prices and projected demand under low and medium technology cost forecasts. In terms of energy generation, PV contributes 8 - 16% of the total mix under those scenarios. However, for all high technology costs scenarios, PV combined capacity from all regions is found to be very low compared to other generators, i.e. 10 GW or lower and PV contributes only 5% of energy.

Given the relatively low penetration of PV by energy in all scenarios, it does not appear likely that there would be significant integration challenges. In terms of hourly dispatch, it is likely that much higher penetrations of variable PV could be reliably accommodated in the JAMALI system. While greater supply-side flexibility and ramping capacities may be required to accommodate hourly variability of PV penetration in low and medium costs scenarios, significant geothermal and hydro can provide relatively constant energy generation and load following, respectively, while flexibility can also be provided by gas plants and more frequent ramping by coal fired plants. Shorter term flexibility may present challenges, but there are a range of technology options with decreasing costs that can provide the fast response required.

Although PV integration into JAMALI of the scale found in the modelling appears both technically and economically feasible, long-term electricity industry planning with PV integration in the Indonesian context requires careful planning and regulation. Key existing challenges include a lack of transparent planning and publicly accessible information regarding costs, technical characteristics, constrains, performance of existing generators and quality (measured) renewable energy resource data.

Meanwhile, another operational challenge would be faced by PLN following the recent MEMR ministerial regulation (MEMR, 2017) due to the obligation to purchase the whole energy generated by PV plants managed by IPPs. To improve the situation, in-depth studies regarding feed-in tariff determination and framework that lead to efficiency improvement and even encourage competition among energy producers, would be beneficial, given the potential benefits of increasing PV integration in JAMALI.

6. Conclusion and further work

This study reviews the current status, and explores the potential for utility-scale PV deployment, in the JAMALI areas. Recent experiences regarding PV deployment, policies and regulations relevant to deployment of large scale PV are described and a number of key challenges for PV deployment are identified. Mapping and analysis of PV output potential and hourly temporal variability for JAMALI areas are presented using data obtained from renewables.ninja based on the NASA MERRA-2 satellite database and the Global Solar Energy Estimator model. This paper also presents preliminary simulations to explore the potential for PV to contribute to an economically efficient generation mix in 2030. PV capacity could vary between 2 GW to 24 GW for the lower demand growth scenario and between 4 GW to 35 GW for other demand scenarios, dependent also on future gas prices.



Average generation cost estimates varied from 41.31 - 62 (US\$/MWh) for all technology, cost and gas price scenarios. Further work on exploring the status and sustainability of long-term electricity planning and power sector development in Indonesia would be of great value for policy makers. Such analysis should include consideration of broader aspects of energy security, future uncertainties and analysis around system robustness with high penetrations of renewables and more detailed technical constraints.

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Appendix 1: Mapping of monthly PV capacity factor across locations in JAMALI in 2015

